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TECHNIQUES, TOOLS, AND REPRESENTATIONS FOR SOLVING
DESIGN PROBLEMS CONSIDERING ANTHROPOMETRY

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by
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ABSTRACT

The quality of available education, solution techniques, and tools for designers considering user body size in the development of products and environments varies widely. The objective of this work is to investigate the current state of affairs in these areas, propose new or improved methods and tools where appropriate, and evaluate these tools.

The multivariate nature of typical problems involving body size and shape—also called anthropometry—makes it difficult to precisely configure a product that meets the needs of a target population of users. As a result, designers may overestimate the robustness of their designs, and many users may be unintentionally excluded by design limitations in some way. This has implications for the safety and comfort of the users, and manufacturers may experience decreased market share and profits as well as regulatory violations for failing to properly consider the spatial requirements of the users of their products. Three objectives/broad impacts of the research are: (1) understand challenges facing appropriate application of anthropometry for design, (2) determine effective alternatives to traditional methods of designing for body size and shape, and (3) develop recommendations that capitalize on the findings for effective alternatives.

To support the three broad impacts, four areas of activity were explored for the research: (1) assessment of human factors/ergonomics (HF/E) education by sampling available course syllabi for courses addressing physical ergonomics in the U.S., (2) assessment of industrial application of practices for designing for user body size and shape via conversations with industrial practitioners in the United States and the Republic of Ireland, (3) experimental evaluation of new representations and tools for visualizing and interacting with multivariate anthropometric data with participants acting as
“designers”, and (4) implementation of the findings in practical recommendations and a prototype mobile application.

Several key results follow from the four areas of research activity, and a few of them are highlighted here. The course syllabi survey showed that anthropometry is covered in the vast majority of courses, but receives an average of only 9% (1.6 days) of lecture time. Most course texts' treatment of anthropometry indicates that students are not provided with adequate tools to properly design for body size due to inappropriate, insufficient, or outdated anthropometric data. The survey of ergonomics practitioners showed that designing for the industry-standard 5th–95th percentile accommodation is a common goal among ergonomics specialists. The survey also showed that both specialists and general design practitioners make use of the traditional Dreyfuss templates (e.g., Measure of Man) despite important limitations on their use. Awareness of principles and tools for designing for body size was the greatest challenge identified by respondents, along with availability of reliable anthropometric data.

Two experimental web-based evaluations of representations showed, among other findings, that employing interactivity in tools for designing for human variability enhanced subjective measures of tool performance, representative humanoid glyphs are insightful and need not be intricate to be effective, and familiar and well-laid-out figures provide the most benefit for designers considering body size. These results are combined with best practices for designing for human variability to develop a set of recommendations and a prototype mobile application for designing for anthropometry.

The impact of the work is far-reaching—offering guidance for developing improved tools for designers, improved comfort and safety for users, and enhanced profit and easier regulatory compliance for manufacturers. The research may find application for a wide variety of products, from cars and aircraft to workstations and hand tools. The research is also relevant to a broad audience, from students and practitioners to architects and product designers.
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CHAPTER I

INTRODUCTION

This dissertation is an investigation of design techniques and tools that enable designers to make decisions about how to configure products and environments for the *anthropometry* of target populations of human users. Anthropometry is a classical compound that literally means “human measures”, and throughout this work the term refers to the physical size and shape of people. There exists wide variability in education and practice in the application of anthropometry. Better understanding of how problems are solved by students in ergonomics courses and design practitioners in industry are key initiatives of this dissertation. A survey of human factors/ergonomics course syllabi and interviews with design practitioners have been conducted to gain insight into the practice of physical ergonomics. Hypotheses regarding the effectiveness of various kinds of design tools and representations are tested through empirical studies of end-users. Two practical implementations of the findings are presented—a prototype of a mobile software application for design and evaluation and recommendations for making efficient decisions in the tradeoff between user fit and the cost or complexity of products or environments.

Most engineered products have been designed to meet particular goals. Often, the quality of interaction between a product and its user is a key performance metric, and a designer concerned with evaluating this interaction must simultaneously consider many factors. What groups of people will use the product? Will these intended users experience comfortable and safe interaction with the product? Does the product meet regulatory guidelines? Is the product cost-effective? These are important questions in the design of the physical interface of products and environments that may be addressed
traditionally by “ergonomics” or “human factors”, broad terms that may refer to a number of different disciplines. In this dissertation, physical ergonomics refers primarily to design and evaluation activities that account for the body size and shape of users, although the term often also includes other considerations such as biomechanics, strength, capability, etc. Design for Human Variability (DfHV) is a subset of physical ergonomics that focuses on quantitative simulation of the variability of users. DfHV best practices are described later. The author’s previous research has explored various aspects of DfHV, which drive the practical implementation of the dissertation findings.

A fundamental task within physical ergonomics and DfHV is dimensional optimization. Dimensional optimization of a product refers to the optimization of the dimensions of one or more aspect(s) of a product to accommodate some desired portion of a target user population (Roe, 1993). Accommodation may refer to physical fit or comfort or other measures of acceptability of the user-device interaction, and physical dimensional optimization is often a key consideration. Typically, dimensional optimization is concerned with variability in users’ physical body dimensions. Sometimes these are referred to as spatial requirements. Dimensional optimization can be achieved by the creation of multiple sizes of a product or adjustability on one or more dimensions of a product. It is important to recognize that either under-specifying a design (e.g., yielding lower cost but accommodating less users than intended) or over-specifying a design (e.g., yielding accommodation for more users than intended but increasing cost) are both undesirable outcomes.

Dimensional optimization is a concern for countless products and environments, but becomes particularly challenging for products with multiple design variables. Such problems are commonplace—cars, airplanes, and workspaces are examples. Manufacturers integrate fit assessments into the design of these complex products; consumers perform similar evaluations during purchase.

Conventional wisdom tells car buyers: “fast, comfortable, cheap—pick two”. When the Mazda Miata MX-5 two-seater was introduced in 1989, Car and Driver named it a 10Best pick, saying “It’s cheap. It works. ... Everybody Loves It.” (Car and Driver, 1990) However a capacious cabin was not one of its virtues, with consumers and reviewers
alike calling it everything from “cozy” to “cramped” (see Figure 1.1). Inspired by Kansei Engineering, Mazda MX-5 chief engineer Takao Kijima describes the intent of the interior design to evoke “the movement and stillness of a samurai’s tearoom” (Kijima and Hirai, 2003). No doubt, the samurai in question was of petite stature! While the Miata has enjoyed enormous success as a result of its performance in other areas, betting on “fast” and “cheap” at the expense of comfort is a gamble few automakers will win without a thorough understanding of the needs of target users (and the compromises they are willing to make). Thankfully, manufacturers of most vehicles carefully consider the needs of their customers and consumers benefit in terms of both comfort and safety. Research in automotive packaging has increased performance in these areas over the past two decades.

1.1 Research Objectives

The primary hypothesis of the work is that common design tools for applying anthropometric data (e.g., templates and tables of percentile values) are inadequate and limit understanding of how to solve multivariate spatial optimization problems for products designed for their users’ body size. These common tools misapply anthropometric data despite important limitations that have been in the literature for decades. The research details shortcomings in existing tools and methods and proposes
improved ways of solving these problems using effective multivariate data representation and interactive tools.

It follows, then, that three objectives and broad impacts of the research are: (1) understand challenges facing appropriate application of anthropometry for design, (2) determine effective alternatives to traditional methods of designing for body size and shape, and (3) develop recommendations that capitalize on the findings for effective alternatives. Each of these objectives is expanded upon in this section.

Research Objective 1: Understand challenges facing appropriate application of anthropometry for design. In addition to a review of available literature on the topic, two other research activities support this objective. First, an assessment of human factors/ergonomics (HF/E) education was conducted by sampling available course syllabi for courses addressing physical ergonomics in the United States. Second, an assessment of industrial application of practices for designing for user body size and shape was performed via one-on-one conversations with industrial practitioners in the U.S. and Ireland. The Irish interviews were sponsored in part by the Centre for Excellence in Universal Design (CEUD) at the Irish National Disability Authority (NDA).

Research Objective 2: Determine effective alternatives to traditional methods of designing for body size and shape. This objective is supported by two web studies. The experimental surveys test new representations and tools for visualizing and interacting with multivariate anthropometric data with participants acting as “designers”. The first study assesses an interactive web interface for exploring anthropometric data as compared with traditional, static tables. The second study assesses various types of representations and designers’ preference for them.

Research Objective 3: Develop recommendations that capitalize on the findings for effective alternatives. Finally, the findings from the other research activities are packaged into practical recommendations for design and a mobile application prototype that capitalizes on interactivity and effective multivariate representations.
1.2 Summary

This dissertation provides guidelines for applying body size for design, an assessment of current education and practice in the area of designing for body size, and recommendations for tools for visualizing human variability. Chapter II provides background in the application of anthropometry for design and review of the literature. Chapter III surveys syllabi for 29 physical ergonomics courses in the U.S. for course content and any texts used in the class to investigate the role of education as a limitation for proper application of anthropometry. Chapter IV presents the results from surveys of 7 ergonomics practitioners in the United States and 11 design professionals in the Republic of Ireland via one-on-one interviews. The purpose of these interviews is to assess designers’ knowledge of anthropometry, ergonomics/human factors, and universal design, and the tools and methods used to support design activities in these areas. Chapter V introduces various visualization techniques that may be applied to design problems involving body size and shape. Chapter VI describes results of two experimental studies in which the techniques were evaluated with students and professionals acting as “designers”. Finally, Chapter VII makes recommendations for practical guidelines and tools for designing for body size based on the results of the previous chapters.
CHAPTER II

BACKGROUND AND LITERATURE REVIEW

This chapter reviews literature on the treatment of body size data, particularly as applied in ergonomics/human factors. The review primarily focuses on the use of body size to design products (e.g., tools, vehicles, or military equipment) or work environments (e.g., a desk in an office). The design of “built environments” such as homes or office buildings is another application of body size that is a facet of architecture. This use is not emphasized in this chapter, but is briefly covered in Chapter IV when discussing interviews with architects and some product designers.

This chapter follows the general progression of body size applied to design in recent years, beginning with early concepts and studies of body size, continuing through design practice during the middle of the twentieth century (e.g., templates), moving on to improved design tools for designing for body size (e.g., digital human modeling and multivariate statistical analysis), and concluding with modern best practices (e.g., the DfHV paradigm and universal design) and continued problems existing in the literature. The purpose of this chapter is to set the stage for discussion of improved, next-generation tools for working with body size data for design.

2.1 Anthropometry, sources, and application

The earliest discussion of detailed proportions of body size come from the first century B.C. and the Roman architect Vitruvius (Pheasant and Haslegrave, 2006). These proportions were famously sketched by Leonardo da Vinci in the sixteenth century A.D. in the *Vitruvian Man*. See Figure 2.1. A few relationships listed in the text of this ubiquitous representation are: “the length of the outspread arms is equal to the height of
a man”, “from above the chest to the top of the head is one-sixth the height of a man”, and “the distance from the elbow to the tip of the hand is is a quarter of the height of a man”. These may be considered the earliest proportionality constants, which scale various dimensions of body size with a common measure, such as stature. These early observations testify to the recognition of the importance of considering the size of people in the products and environments they use.

2.1.1 Sources of anthropometry

Surveys of the the body size of individuals began to be conducted more than 200 years ago, primarily for the purposes of distinguishing among races and ethnic groups of humans, to identify criminals, and to make medical diagnoses (Roebuck, 1995). As early as World War I, the military began to study the size of its service members. Primarily during and following World War II, these studies began to be used to improve the design of clothing, personal equipment, and aircraft cockpits. The 1946 U.S. Army men survey was the first extensive survey conducted by the Army for the purpose of determining body size information for the design of equipment (Department of Defense, 1991). In the years since, 15 major anthropometric surveys have been conducted with men and women from various military services. The most recent available military data comes from the
1988 Army Anthropometric Survey (ANSUR) (Gordon et al., 1989), although new data are currently being collected for a joint Army and Marine anthropometric survey, called ANSUR II/MC-ANSUR (Paquette et al., 2009).

While they are typically very detailed, military databases should not generally be used to design for civilian populations because they do not represent the full range of variability in such groups. For instance, military populations generally tend to be fit and young, unlike a general civilian population. Surveys of civilian anthropometry have been conducted for countries all over the world (Jürgens et al., 1990). Such surveys typically include basic measures such as stature and body mass.

In the United States, the National Health and Nutrition Examination Surveys (NHANES) are an ongoing effort of the Centers for Disease Control and Prevention (U.S. Centers for Disease Control and Prevention, 2008). This effort began in the 1960’s, with the National Health Examination Surveys (NHES). NHES I, II, and III examined various aspects of the population throughout the 1960’s and gathered such measures as age, sex, stature, and weight. NHANES I, II, and III continued throughout the 1970’s, 1980’s, and 1990’s by collecting similar anthropometric information, along with additional data regarding nutrition. HHANES, or the Hispanic Health And Nutrition Examination Survey, examined this same data for the Hispanic population in the mid 1980’s. Since the mid 1990’s, NHANES data has been collected on an ongoing basis; the data are released every two years.

Another database of civilian anthropometry for design is the Civilian American and European Surface Anthropometry Resource (CAESAR) (Robinette et al., 2002). The goal of the CAESAR project was to develop a resource of three-dimensional body surface scans, along with several traditional anthropometric measurements. While the resource includes over 4000 sets of data from several countries, it is not representative of a single target population that is useful for design (e.g., U.S. Army). Instead of providing an absolute sense of body size for design, CAESAR may be used as a tool to explore body shape variation relative to sizes specified by some other resource.

A distinct disadvantage of most civilian anthropometric data is their limited scope. Typically, the data relevant for human variability design are confined mostly to stature.
Figure 2.2: Accommodating the statistical extremes of a population can be very costly. In the figure, a nearly 30% increase in the measures of a product are required for only a 10% increase in accommodation.

and weight. While these two measures are able to represent a large portion of the variability in a target population, they do not give the resolution attainable with ANSUR or CAESAR data. Parkinson and Reed (2009) describe one technique for applying the relations apparent in the ANSUR database for a wide variety of measures to civilian databases with fewer available detailed measures.

2.1.2 Application of anthropometry for design

There is an inherent tradeoff between accommodating a large range of body sizes and minimizing cost, weight, or other product performance parameters. It is the role of a designer to properly configure a product or environment to meet the needs of an adequate range of the target user population. Either over-specifying a problem (e.g., specifying extra adjustability or more sizes than necessary) or under-specifying a problem (e.g., one-size-fits-most) are not usually optimal configurations. Figure 2.2 illustrates the balance between accommodating the variability in target users and the cost for providing that accommodation. For measures that are approximately normally distributed (e.g., measures of length like stature, leg length, arm length, etc.), accommodating individuals in the statistical extremes of a population can be very costly. As a result, designers often aim to accommodate 90% or 95% of the variability. This concept has been known for decades—a similar figure appears in Hertzberg (1955).
Early techniques for considering the body size of users in spatial design tasks consisted of basic templates of the human form. Recognizing an absence of practical tools available to designers, Henry Dreyfuss introduced the concept of “Joe and Josephine” in his 1955 classic on industrial design, *Designing for People*. Figure 2.3 shows one of the original Joe and Josephine drawings (Dreyfuss, 2003). Dreyfuss provides at least two reasons for the creation of the male and female archetypes: (1) “they remind us that everything we design is used by people, and that people come in many sizes and have varying physical attributes”, and (2) “it was necessary to determine the extreme dimensions, for we must consider the variations from small to large in men and women”. The templates provide a few key standing and seated dimensions for small and large men, women, and children. Such templates were used to find design limits for target levels of accommodation.
Dreyfuss published *The Measure of Man* in 1960, which compiled simple human figure templates for men, women, and children, along with several tables and other guidance for designing physical environments for users (e.g., required forces, space requirements, etc.). The guide was intended to be a single reference that was readily accessible and applicable for product designers and engineers. The guide has been revised in recent years, and a “percentile man” from the 2002 revision of *The Measure of Man and Woman* is shown in Figure 2.4. Henry Dreyfuss Associates published *Humanscale* in the 1970’s, which used rotary dials and other pictorial selectors to present information on body size and capability (Diffrient et al., 1981).

Before the advent of personal computers, physical articulated drafting templates were constructed in a range of sizes (e.g., from 1/20th scale to full size) to virtually evaluate the interaction of the user with its environment. Figure 2.5 shows a sketch of physical drafting
templates (Roebuck, 1995). Digital human modeling, discussed later in Section 2.3.2, largely supplanted the use of drafting manikins for design.

The general use of templates for design has continued in wide use for decades. One of the main advantages of templates is the intuitive display of design dimensions on representations of the human form. It is quite easy, even for a novice designer, to locate relevant dimensions and reference extremes to be considered in a design. However, this simplicity comes at a cost—accuracy. The next section discusses some limitations of templates and percentile methods in general.

2.2 Limitations of the template/percentile approach

Design problems typically encountered in practice are multivariate in nature—for instance, to fit in a car, a person must ensure that the car will accommodate their hip breadth, leg length, and head. In a multivariate problem, accommodation may be assessed on many device parameters simultaneously, but a user can be disaccommodated only once. For instance, if a user does not fit on parameter A, then it does not matter if that user fits on parameters B and C since they are already disaccommodated.

A misperception among some designers is that people are generally average on most dimensions. However, experience shows that people are made up of proportions that
may differ greatly from average. Some people have tall torsos and short legs yet still maintain average stature. The notion of a “percentile man” is fundamentally false. Using templates or univariate percentiles of anthropometric data for multivariate problems will result in accommodation for a significantly smaller portion of the target user population than intended.

Such limitations of template approaches for multivariate problems were known practically since their inception. While noting that the assumption of the “percentile man” is commonplace, Hertzberg (1955) dismisses the fallacy. He presents results from a study conducted in 1953 that shows that when a group of Air Force flying personnel are filtered by averageness, only 3.5% are average on a combination of three measures. That falls to 0.69% for five measures and 0% for 10. That means that if a product were designed for the average user on just three dimensions, only 3.5% of users would be able to use it as intended, according to the study.

Moroney and Smith (1972) demonstrated this phenomenon again by similar reasoning and a similar conclusion—compounding the results of limits for multiple univariate measures resulted in far less than the desired accommodation when all measures were considered simultaneously. Robinette and McConville (1981) again demonstrated the fallacy of “the percentile man” and that an individual is not average on all dimensions.

These results are shown graphically in Figure 2.6, which compares two populations. The figure on the left shows a theoretical population with no variability in proportion; the “percentile man” concept assumes the existence of such a population. The figure on the right shows a real population that exhibits variability in proportion. The figure on the right demonstrates: (1) the imperfect correlation between two measures of anthropometry (i.e., users with dimensions not all belonging to the same percentile), and (2) the resulting effect that many people are unintentionally excluded when limits on different measures are combined. A designer expecting to achieve 95% accommodation for stature and bideltoid breadth combined by looking up 95th-percentile stature and 95th-percentile bideltoid breadth will in fact only achieve 91% accommodation in this case. The measures in the figure come from the 1988 ANSUR data.
Figure 2.6: Illustration of two dimensions, stature and bideltoid breadth, of a 1000-member population, wherein 5% cutoffs have been imposed for each measure. Points located in the red-shaded areas represent excluded people, and those in blue represent accommodated people. On the left, an idealized population exhibits no variability in proportion and 95% are accommodated as expected. On the right, variability is included; combining the limits results 91.1% accommodation, not 95% as expected.

Other limitations of templates are the inability to reconfigure them for populations other than the one from which data were collected—or to determine who the original data represent at all. Frequently, only 5th-percentile and 95th-percentile measures are given (or “small” and “large” values), which make it difficult to design for other ranges of anthropometry.

2.3 Improvements in available tools

A few techniques have emerged in recent decades that allow for more accurate solution of multivariate problems: principal component analysis (Zehner, 1993; Bittner, 2000), digital human modeling (Porter et al., 1993), and a combination of the two (Lockett et al., 2005). These tools are discussed in this section.

2.3.1 Multivariate statistical analysis

Methods using Principal Components Analysis (PCA) have been shown to be effective for multivariate design (e.g., Hudson et al., 1998; Lockett et al., 2005). Such methods find orientations of maximal statistical variance, using correlation matrices and factor loadings, to construct representative cases (i.e., compilation of anthropometric measures)
for evaluation. These types of analyses yield many (e.g., 17 in Bittner (2000)) extreme cases that are used to evaluate the design, rather than just two percentile limits. If all are of the extreme cases are accommodated, then the engineer expects to achieve the level of accommodation equivalent to the amount of anthropometric variability encompassed by the selected manikins.

2.3.2 Digital human models

Digital human modeling, or DHM, refers to the use of computerized manikins for design. In many ways, DHM is the modern counterpart of two-dimensional drafting templates (e.g., Figure 2.5), but offers many more advanced features such as automatic anthropometric scaling and posturing, vision and reach assessments, and integration with CAD packages (Siemens PLM Software, 2012). DHM is commonplace today as a design tool at companies with a dedicated focus on physical HF/E—for instance laying out seating and instruments in automotive or aircraft interiors (Reed et al., 2005; Wegner et al., 2007; Duroch, 2011). Digital human modeling may be used either for univariate or multivariate design—for multivariate design, a “cadre” of digital manikins that accurately represent the variability in a population may be used following the PCA technique described in the previous section.
Application of computer-aided design (CAD) to digital human modeling began in the 1960’s with the goal of enabling evaluations of postural comfort, clearances, reach, and vision (Porter et al., 1990). Early implementations were largely developed for specific applications or with research funding for a particular organization. For instance, BOEMAN was developed by Boeing for checking cockpit layout, BUFORD offered a simple model of an astronaut for Rockwell International, and COMBIMAN was developed for the U.S. Air Force to aid in the design and evaluation of aircraft crew stations (Porter et al., 1990). Development of SAMMIE in the 1960’s was a notable exception—this platform was intended for general ergonomics use. Figure 2.7 shows an early SAMMIE workspace evaluation.

Jack, Santos, CATIA Human, and AnyBody are four modern DHM programs in wide use (Siemens PLM Software, 2012; SantosHuman Inc., 2012; Dassault Systemes, 2012; AnyBody Technology A/S, 2012). Figure 2.8 shows Jack being used to evaluate an aircraft cockpit maintenance task.
While digital human modeling can be a powerful evaluation tool—even able to perform complex multivariate design tasks for the capable designer—the tool often still suffers limitations similar to traditional two-dimensional template techniques. Unlike traditional templates or percentile data, DHM disguises the link between anthropometry and performance because of the impressive visual representations that can be generated. DHM is useful for many design activities, such as preliminary design or identifying design improvements, but should not be viewed as a catch-all solution for modern HF/E design as currently implemented (Chaffin, 2005).

2.4 Design for Human Variability

Design for Human Variability, or DfHV, is a relatively new and fundamentally different way of thinking about the physical HF/E design problem. In many ways, DfHV is a pragmatic approach toward designing for people and includes best practices that have emerged in the literature over the years. This section covers some of the key components of DfHV and the challenges these components seek to address. These concepts have been largely addressed in the author’s previous works.

As with traditional ergonomic assessments, accommodation levels for given target user populations are an essential performance metric for any DfHV problem. In most assessments of accommodation, the state of accommodation is binary; users are either accommodated, and able to fit the device, or disaccommodated, and unable to fit the device. There is no compromise in which a user can be only slightly disaccommodated but still satisfied.

2.4.1 The design process

Methods using anthropometric data to predict user requirements are extensive (Roe, 1993; HFES 300 Committee, 2004; SAE International, 2009). The Human Factors and Ergonomics Society (HFES) have published their Guidelines for Using Anthropometric Data in Product Design (HFES 300 Committee, 2004). It describes methods for using anthropometry in ergonomic design, with an emphasis on products with an adjustable
dimension. It suggests a five-stage process for ergonomic design. Various aspects of these steps are discussed below. The steps are:

1. Define the problem and relevant measures
2. Define the target audience
3. Identify the database and relevant considerations
4. Select cases (boundary manikins)
5. Apply cases to the design

2.4.2 Discrete sizing and adjustability as accommodation techniques

The process of developing a model to represent the entire target population and then applying that model to the design (Steps 4 and 5 of the HFES Ergonomic Design Process) are critical for determining user accommodation. A single, nonadjustable size is usually not recommended. Consequently, strategies such as sizing and adjustability are often utilized.

Specification of multiple discrete product sizes is one suitable solution method for many applications (e.g., McCulloch et al., 1998; Garneau and Parkinson, 2008). Clothing and footwear are common examples of this strategy, but it is also used when adjustability might be too complicated or costly. Garneau and Parkinson (2011) investigate several considerations for designing a product with multiple sizes, including the effect of setting particular design goals (e.g., average versus minimum performance optimization) and different size distribution techniques (e.g., equal people per size versus equal spacing across the variability in dimensions).

Many dimensional optimization problems consider products of a single size with adjustable dimensions. Different methods for specifying adjustability offer various advantages and involve differing levels of complexity (Garneau and Parkinson, 2011). There are two general approaches to achieving user accommodation: manikins and population models. Combinations of these methods are also possible and offer important advantages.
2.4.3 Manikin-based approaches

“Manikin” is a general term referring to a representation of a set of anthropometry. For instance, the use of “manikins” was discussed in Section 2.1.2, where they were called “templates”, and in Section 2.3.2, where they were referred to as “digital human models”. A “manikin” might also refer simply to a set of anthropometry to be considered in a design without a graphical representation. A “boundary manikin” or “boundary case” refers to a body geometry that lies at the limit of acceptability. For a design problem in which only one body dimension is relevant and both “small” and “large” people must be considered, only two cases are typically used to describe the upper and lower limits of acceptability. For example, to accommodate 95% of the population, one might use the 2.5th-percentile and 97.5th-percentile values of the measure of interest as boundary cases.

In general, accommodation at the boundary is thought to ensure accommodation at interior points, as long as the adjustability of the product dimension is continuous (HFES 300 Committee, 2004). Note that since the distribution of body sizes is continuous, the specific level of accommodation (95%) could be achieved by targeting any number of segments (e.g., population minimum to 95th percentile; 2nd to 97th percentile). Generally the range is selected to minimize the amount of adjustability or material (and therefore cost) required. For a single variable this is generally the lower (population minimum to 95th percentile) or central (2.5th to 97.5th percentile) portion of the distribution.

Since stature and weight data are the most easily obtained and therefore prevalent in databases, distributions of those variables are often used to determine the sizes of the “small” and “large” manikins. While stature and weight or body mass index (BMI), a measure of weight-for-stature, are good indicators of overall size, they are not typically the measures useful for a particular design. Other measures such as leg length, seated eye height, arm length, etc., are more relevant. As such, it is helpful to have knowledge of the length of the relevant dimension(s). If this information is unavailable, proportionality constants are often used (Drillis and Contini, 1966). As shown in Figure 2.9, these represent the average length of a particular body segment as a proportion of stature.
Figure 2.9: Body lengths expressed as a proportion of stature. Proportions derived from Drillis and Contini (1966) are shown on the left, and proportions derived from Gordon et al. (1989) are shown on the right. (similar constants represented by the Vitruvian Man were presented in Figure 2.1). This approach is imprecise, due to the fallacy of the “percentile man”.

Basic assessments of accommodation in dimensional optimization rely only on the anthropometry of the target user population and do not account for actual user behavior or anthropometry-independent effects (e.g., Bittner, 2000; HFES 300 Committee, 2004). More advanced assessments of accommodation also consider variability in usage and fit unrelated to body dimensions (Kolich, 2003; Reed and Flannagan, 2000). For instance, two automobile drivers of identical size are not likely to choose identical seat positions due to each driver’s unique preferences. Realistic posturing is required for any use of manikins in design (Parkinson et al., 2007). For some applications, such as those in the automotive and aerospace fields, standard posturing models have been developed through experimental testing. An example is the Cascade Prediction Model for predicting automobile driving posture (Reed et al., 2002). Alternatively, it may be possible to sample a small number of users representing boundary manikins to determine average behavior with results similar to a regression analysis with a larger sample size (Manary et al., 1998).
2.4.4 Population model approaches

An alternative to the boundary manikin approach is the task-oriented percentile model (e.g., Roe, 1993; Dannhaus et al., 1977). A designer implementing this approach would observe participants representative of the target user population as they interact with prototypes of the situation of interest. The requirements of the user population (e.g., the required adjustability) are then defined by the selections or capabilities of the desired proportion of users. Both a sufficiently large representative sample population and a workable prototype are required. This approach forms the basis for the SAE International recommended practices (SAE International, 2009), which are used for vehicle design.

These models are an improvement on manikin-based approaches in some ways, since they specifically model the outcome measure of interest (e.g., driver-selected seat position in a car or rider-selected saddle height on a bicycle), rather than trying to predict the population distributions of those outcomes from boundary cases defined by anthropometry. However, they require extensive human-subject data from a similar task scenario and they are essentially univariate, dealing with only a single outcome measure (e.g., seat location or reach) at one time. Population models are not easily adapted to other conditions, tasks, or populations; they may quickly become outdated as these qualities change over time.

2.4.5 Hybrid approaches

Methods that combine the use of manikins with population models are termed “hybrid” approaches. The foundation for any hybrid approach is a preference model that uses experimental data from a preference study of a small group of sample users interacting with a prototype of the device being designed to correlate the outcome measure of interest with some measure(s) of related anthropology. This is similar to the population model approach in that it models behavior directly. It also exhibits a strength of the manikin approach in that it allows the model to be extrapolated to populations different from the one from which the data were gathered. Care should be taken, however, to ensure that the small preference study population has characteristics similar to the target population. Furthermore, the preference study should include users at the extremes of the target
population to ensure that their behavior is sampled, because it is those users who are most often disaccommodated.

One simple hybrid approach uses a linear regression model to predict an outcome measure deterministically from some measure of anthropometry. Boundary manikins that have extreme anthropometry (e.g., 5th and 95th percentile stature), are selected and the anthropometry of these manikins are used as predictors in the regression models to determine adjustability limits of the outcome measure (e.g., Flannagan et al., 1998; Reed and Flannagan, 2000). Unfortunately, this procedure results in a practice in which artifacts are designed to meet the average behavior or preference associated with individuals of a particular body size. For instance, if designing an adjustable-height chair, two people with identical stature would be predicted to select the same chair height in this implementation of the hybrid method. This ignores the residual variance in the experimental data, which describes how the preference of an individual of a given size differs from the mean.

Recent research has expanded on this basic hybrid method, examining the variability in use that cannot be predicted by body size or geometric constraints. To address this, a second component is included in the preference model that considers preference unrelated to body dimensions. Reed and Flannagan (2000) investigate the effect of variability unrelated to body dimensions on driver seat position and eye location in an automobile. Garneau and Parkinson (2011) compare outcomes associated with manikin-based, population, and hybrid approaches.

The anthropometry-independent preference component is included by retaining a measure of the spread of data about the mean regression line. This may be quantified by a measure of residual variance. The root mean squared error (RMSE) is such a measure and can be understood as the standard deviation of the normal spread of data about the mean regression line (i.e., $\sigma = \text{RMSE}$). Virtual populations may then be used to assess the “fit” of virtual users in quantitative simulations as shown in Figure 2.10. A virtual population is a collection of many anthropometric data points (e.g., 1000) that, as a whole, characterize a target user population. The virtual population can be obtained by two methods:
Figure 2.10: Including a measure of anthropometry-independent preference (i.e., scatter about the mean) to create more representative models of user behavior enhances estimates of accommodation. In the figure, 95% accommodation is attempted using a model including scatter and one modeling only mean behavior—actual accommodation is listed in parentheses. The mean behavior model predicts too little adjustability for the device dimension to achieve the target accommodation.

- Random sampling of members of a larger representative database (e.g., NHANES, U.S. Centers for Disease Control and Prevention (2008))

- Random sampling of normal distribution(s) of the desired anthropometric parameter(s) with a specified mean and standard deviation. This requires an assumption of normality in the anthropometric variables.

In Garneau and Parkinson (2009), results for a case study show that accommodation was increased from 83% to 95% using a model that included anthropometry-independent preference, when compared with a model that modeled only mean preference (without the stochastic component). See Figure 2.10 for a depiction of a 1000-member virtual population wherein some device dimension is correlated with some measure of anthropometry, along with lines depicting 95% cutoffs for the case of mean behavior (orange) and behavior with anthropometry-independent preference included (blue).

### 2.4.6 Multivariate considerations

A multivariate problem is one in which more than one product adjustment is possible and more than one user dimension is relevant. For such a problem, one of the multivariate techniques from Section 2.3.1 might be used. If a “cadre” of boundary manikins is
generated and the device is configured to accommodate all of its members, then the engineer expects to achieve the level of accommodation equivalent to the amount of anthropometric variability encompassed by the selected manikins. However, this approach only works in extremely constrained cases (Parkinson and Reed, 2006) and the ramifications of disaccommodating one or more manikins are unclear.

For multidimensional problems, an approach using a population model might be particularly helpful. This is because such a model considers only the outcome of anthropometric variability, such as eye location in an automobile, instead of the factors causing that variability, such as torso length or fore-aft seat adjustment (which can be predicted by stature). Although the results are typically limited to the problem at hand, this focuses the work of the designer.

2.5 Universal design

While DfHV is concerned with explicitly incorporating anthropometry to design products for target accommodation, universal design approaches inclusion of the user from a different perspective. The term “universal design” was coined by architect and wheelchair user Ron Mace in the early 1980s (Bremer et al., 2002). He defined universal design as, “The design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design”.

Later, in 1989, Mace went on to create the Center for Universal Design at North Carolina State University (Story, 1998). The intention of the Center for Universal Design is to assist designers in creating products and designs that are usable by everyone. Their research focuses on creating design solutions that will benefit as many users as possible. Recent years have seen an explosion of growth in research related to universal design across the world.

2.5.1 Principles of universal design

In 1997, the Center for Universal Design published the Seven Principles of Universal Design, which still serve as the primary guidelines for many designers intending to create
universal designs around the world (Preiser, 2008). The principles are listed in Table 2.1, with the definitions from Connell et al. (1997).

<table>
<thead>
<tr>
<th>Principle</th>
<th>Principle Name</th>
<th>Principle Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equitable Use</td>
<td>The design is useful and marketable to people with diverse abilities</td>
</tr>
<tr>
<td>2</td>
<td>Flexibility in Use</td>
<td>The design accommodates a wide range of individual preferences and abilities</td>
</tr>
<tr>
<td>3</td>
<td>Simple and Intuitive</td>
<td>Use of the design is easy to understand, regardless of the user’s experience, knowledge, language skills, or current concentration level</td>
</tr>
<tr>
<td>4</td>
<td>Perceptible Information</td>
<td>The design communicates necessary information effectively to the user, regardless of ambient conditions or the user’s sensory abilities</td>
</tr>
<tr>
<td>5</td>
<td>Tolerance for Error</td>
<td>The design minimizes hazards and the consequences of accidental or unintended actions</td>
</tr>
<tr>
<td>6</td>
<td>Low Physical Effort</td>
<td>The design can be used efficiently and comfortable and with a minimum of fatigue</td>
</tr>
<tr>
<td>7</td>
<td>Size and space for approach and use</td>
<td>Appropriate size and space is provided for approach, reach, manipulation, and use regardless of the user’s body size, posture, or mobility.</td>
</tr>
</tbody>
</table>

Most designers today agree that universal design is achievable, and creating a universal design often costs no more than creating a typical one if universal design principles are considered early enough in the design phase (Mace et al., 1991). Additionally, the benefits of universal design are not limited to those who have permanent disabilities. For instance, closed captioning benefits those without auditory disabilities at times when ambient noise is too loud to hear a television (for example, at an airport or other public place). A second example is accessibility to built environments provided by wheelchair ramps. Such ramps are primarily intended to make it possible for physically disabled people to enter a building on their own, but ramps also benefit those without disabilities by providing an easy means to wheel cargo, strollers, shopping carts, and furniture in and out of buildings (Mueller, 1998).
As people age and face an increasing number of limitations, there exist ethical, practical, and financial imperatives to continue to provide an aging population with designs that are accessible and safe. The United Nations predicts that 22% of the world’s population will be over the age of 60 by 2050, and the Federal Interagency on Aging Related Statistics predicts that 20% of the U.S. population will be over the age of 65 by 2030 (Ehrenman, 2005). Choosing to ignore such a large percentage of the population would surely limit the relevance and potential revenue of a product or environment.

### 2.5.2 Differences between ergonomics and universal design

An examination of the literature indicates a subtle difference between most human factors or ergonomics activities and those surrounding universal design. In particular for product design, the difference is in solution strategy and the point in the design process at which the designer considers user requirements. Training, literature, and practice in human factors and ergonomics are typically focused on examining a proposed interaction or design topology and determining the ideal manner in which this should occur. For example, tabulated strength capability measures for a population might guide the designer in determining how much spring force would be appropriate for a self-closing door. Similarly, data on the range of body sizes in target users might indicate appropriate adjustability in a seat.

In contrast, successful examples of universal design are not the result of an optimized topology. Instead, they represent a re-examination of the problem during the concept generation phase of the design process. Rather than determining the amount of adjustability, number of sizes, or appropriate weights, the most effective universal design proposes a novel solution where traditional limitations are irrelevant.

As a practical matter, the remainder of the current work is largely concerned with exploring the first solution strategy following typical strategies for working with anthropometry and offering guidance and proposed tools that support it. However, regardless of strategy, it is important that designers understand the user requirements early in the process and consider the user and intended purpose throughout.
2.6 DfHV best practices and challenges

This section summarizes best practices and challenges when designing for human variability. They are primarily key points from Section 2.4. They are some of the most important concepts to be considered when preparing recommended guidelines or tools for design.

2.6.1 Best practices

Carefully consider the target population

Designers should exercise caution in selecting anthropometric data that represents the users for which they are designing. For instance, military data should only be applied to military target users—if designing for the general U.S. population, for instance, better representative data should be located or constructed using one of the methods for synthesizing population anthropometry mentioned in this chapter. Additionally, populations can change over time and designers should not only select data that represents target users today, but also considers target users of the future. Secular trends are among many factors influencing distributions of anthropometric dimensions that a designer must consider as additional sources of variability; others include age, gender, ethnicity, and race (U.S. Centers for Disease Control and Prevention, 2008; Nadadur and Parkinson, 2010). The secular increase in BMI over the past few decades is shown in Figure 2.11 (de Vries et al., 2010).
Model actual user behavior

The foundation for any robust approach to designing for human variability is a preference model that uses experimental data from a preference study of sample users interacting with a prototype of the device being designed to correlate the outcome measure of interest with some measure(s) of related anthropometry. The simplest hybrid approach uses a linear regression model to predict an outcome measure deterministically from some measure of anthropometry. Boundary cases are selected that have extreme anthropometry (e.g., 5th and 95th percentile stature), and the anthropology of these cases are entered into the regression models to determine adjustability limits of the outcome measure.

Perform virtual fitting

Recent efforts have used virtual populations to assess the “fit” of virtual users in quantitative simulations (e.g., Parkinson et al., 2007; Garneau and Parkinson, 2009). A virtual population is a collection of many anthropometric data points (e.g., 1000 sets of stature, BMI, or other relevant parameters) that, as a whole, characterize a target user population. The use of virtual populations allows for virtual fitting trials, which assess accommodation, or fit, of the virtual population on one or more product parameters. A virtual fitting trial uses the anthropology of each member of the virtual population to predict the outcome measure for each member, which is determined by the linear regression model developed from the preference study. A second, stochastic term, defined by random sampling from a normal distribution with standard deviation equal to the RMSE of the regression, is added to the mean predicted outcome measure to emulate user preference unrelated to anthropometry.

Simultaneously consider multiple dimensions

Many DfHV problems are multidimensional (i.e., more than one product adjustment is possible and more than one user dimension is relevant). For multidimensional problems, an approach using a population or virtual fit model is effective for quantitative analysis. This is because such a model considers only the outcome of anthropometric variability, such as eye location in an automobile, instead of relying strictly on the kinematics of
the user (i.e., anthropometry) and environment, such as torso length or fore-aft seat adjustment (which can be predicted by stature). This greatly simplifies the specification of required adjustability because subjective designer assessments of the connection between anthropometry and fit are discounted.

2.6.2 Challenges

From the foregoing discussion, it may be inferred that there are several factors that complicate DfHV analyses. These factors constitute challenges that necessitate further research into better representations and decision-making tools for designers. Each of these factors is summarized individually here.

Preference uncertainty

The importance of including preference not predicted by anthropometry in DfHV solutions has been the focus of the author’s previous research. As discussed earlier and demonstrated in Figure 2.10, inclusion of a regression-based stochastic component (i.e., anthropometry-independent preference) in virtual fitting models yields better estimates of design dimensions and accommodation. However, recognizing that uncertainty in this measure exists, quantifying it, and accounting for it in an analysis is a challenge that is often not considered in designing products for their users.

Considering multiple dimensional spaces

Many engineering problems incorporating optimization have clearly defined inputs and outputs, with associated “design” and “performance” spaces (Rao, 2009). Objective functions may be used to assess performance across the design space by employing a variety of methods. In DfHV problems, it is insightful to consider at least two—the “anthropometry” space and the “design” space. The motivation for this construct relates directly to the foregoing discussion and is addressed here.

Visualizing anthropometry in its own space underscores the importance of anthropometry-independent parameters on fit. Without it, designers are more likely to neglect the distinctness of anthropometry and design dimensions, and assume a
one-to-one correspondence between the two. For instance, if a designer aims to determine optimal bicycle saddle height range, they might assume range in hip height across the population is equivalent to range in required saddle height. This assumes a simplistic preference model that neglects actual user behavior and any sort of preference.

Often a designer wishes to maximize accommodation but minimize required adjustability because of its association with cost. In the decision-making process, the designer may ask the following two questions: (1) where do accommodated and disaccommodated users lie across the distribution of anthropometric measures?, and (2) how does altering design dimensions impact accommodation? These questions require simultaneous consideration of the anthropometry and design spaces. For one-dimensional problems, all of this information may be combined into one two-dimensional representation, but this is impossible for higher-dimensional problems.

Displaying anthropometry in its own space while also visualizing other design dimensions clearly adds a layer of complexity to decision-making tasks, and makes visualization more complicated. However, it is necessary for designers to have insight into both of these spaces and the relationship among them. Visual exploration of the two spaces for making design decisions is a primary area for investigation in this work.

Satisfying conflicting objectives

In addition to multiple measures of anthropometry, designers must consider multiple outcome measures, such as population accommodation (on fit, visibility, and/or reach), cost of adjustability or sizes, and regulatory compliance. Solution methods specifically suited to the stochastic virtual fit method of designing for target populations have been explored in the author’s previous work. Examples include Garneau and Parkinson (2008), which examines the tradeoff between cost and number of discrete sizes of a product, and Parkinson and Garneau (2011), which demonstrates how optimal levels of performance and regulatory compliance may be achieved, with an application to vehicle head restraints.
2.7 Chapter summary

This chapter covered common tools for solving problems involving anthropometry, including templates, percentile data, digital human models, and population models. It also covered common sources of U.S. anthropometry, including ANSUR and NHANES. Limitations to traditional methods were discussed, chiefly the fallacy of “the percentile man” and the solution of multivariate problems. Design for Human Variability was introduced as a pragmatic approach to considering body size variation that offers solutions to some problems of traditional methods. Design for Human Variability is made up of four fundamental principles or best practices: (1) carefully consider the target user population, (2) model actual user behavior, (3) perform virtual fitting, and (4) simultaneously consider multiple dimensions of variability. Specific challenges of Design for Human Variability were also identified, including: (1) considering uncertainty introduced by user preference, (2) considering multiple spaces, and (3) satisfying conflicting objectives. Universal design was also introduced as a rethinking of the strategy for the design of products or environments for users of all abilities.

Despite known limitations for traditional methods, univariate methods are still regularly misapplied in the literature—for instance, workstation design in Das and Sengupta (1996) and tractor seat design in Mehta et al. (2008). Meanwhile, users suffer from inadequate fit that impacts both comfort and safety because practicing engineers have not been properly trained in the application of appropriate, robust methods for designing for human variability. These errors may be due in part to inadequate or misleading discussions of application of anthropometry in common textbooks (e.g., Sanders and McCormick, 1993; Chenguler et al., 2004). The next two chapters investigate the state of ergonomics education and industrial practice via surveys and interviews with design practitioners. The chief aim of these activities is to better understand how to develop tools or disseminate information to improve practice in the area of designing for human variability by identifying any weaknesses or challenges in education or industry.
CHAPTER III

PHYSICAL ERGONOMICS IN EDUCATION

Given the examples found in the literature and industry, many ergonomics practitioners today lack the skills and tools to adequately solve problems involving dimensions of user body size and shape. This situation is not due to a lack of available educational programs. The Human Factors and Ergonomics Society (HFES) currently lists 74 universities in its Directory of Human Factors/Ergonomics Graduate Programs in the United States and Canada (Human Factors and Ergonomics Society, 2012).

One possible culprit for deficiencies in practitioners’ skills is the content of available curricula. The programs listed by the HFES Directory cover a wide variety of topics. From “safety engineering” and “human decision-making” to “musculoskeletal disorders” and “display design”, there are dozens of subjects that students in human factors/ergonomics may choose to learn. However, it could be asserted that with this great breadth of subject matter comes a commensurate lack of depth of coverage in any particular area. It could also be asserted that even if entire courses were devoted to physical accommodation, educational resources (e.g., textbooks) currently in broad use would not support accurate assessment of problems involving multivariate anthropometry.

To investigate the role of education as a possible limitation for proper application of anthropometry, the first part of this chapter presents a survey of college courses in physical ergonomics to assess their scope and resources currently in broad use. The second part of the chapter discusses implications of the study findings and literature for improving human factors/ergonomics education.
3.1 Education survey

The state of education in physical human factors/ergonomics must first be assessed. Two chief aims are to verify the assertions that: (1) the scope and time spent on relevant topics in college programs covering physical ergonomics may contribute to weak understanding of how to solve problems involving anthropometry and accommodation, and (2) contemporary textbooks in broad use do not provide the tools necessary to properly account for the anthropometry of target user populations. To achieve the first aim, course schedules are necessary. To achieve the second aim, it is necessary to first determine the most commonly used textbooks and then assess their treatment of anthropometry.

3.1.1 Survey methods

Setting the boundaries of this survey is an important first step. As mentioned previously, human factors/ergonomics is incredibly broad and diverse. The skills required of a researcher in cognitive human factors designing effective displays greatly differ from those required of an industrial ergonomist configuring an office chair. Therefore, a distinction is made between cognitive human factors and physical ergonomics. This distinction is often apparent in the structure of college programs and courses. This study examines only physical ergonomics—including topics such as work design, anthropometry, and occupational biomechanics. A detailed list of topics considered for this study appears later in Figure 3.2.

Information about course structure and content for physical ergonomics courses in the United States was obtained by an internet search and email requests sent to instructors of such courses. Courses and instructors were selected from the HFES Directory (Human Factors and Ergonomics Society, 2012). Instructors were selected by examining their research interests—either via their HFES listing or an internet search—and retaining those with some connection to physical ergonomics. An email request was sent to 59 instructors that specified the goals of the study and the limitation on physical ergonomics (see Appendix B). Application and approval from an Institutional Review Board was not required because the research does not include the use of “human subjects” as defined
Usable syllabi were gathered for 29 courses taught by 21 instructors at 18 universities (the response rate of the email request was 36%). Most of the courses were surveys or introductory in nature; however, this was not a requirement for the study. Both undergraduate and graduate level courses were considered. In order to be included in the study, the syllabi for the courses had to indicate at least one lecture on one of the physical ergonomics topics appearing in Figure 3.2. Classes that were entirely biomechanics (except occupational biomechanics) or occupational safety were excluded. If multiple syllabi were received for the same course, the most recent one was used. In the results, interpretation of topics listed on syllabi was avoided in favor of a literal search. For instance, “stress” or “fatigue” might be considered “work physiology”, but this assumption was not made if the term “work physiology” was not included.

Figure 3.1 indicates the departmental affiliation for the course syllabi. As expected, most courses were affiliated with Industrial and Systems Engineering, although a handful were also affiliated with other departments.
Ellis and Goldberg (1992) conducted a similar survey in 1992, with a few slight differences. In their study, only syllabi for introductory courses were sought. That study did not limit its inquiry to physical ergonomics; of the 28 topics they identified via syllabi received, 7 belonged to the list of physical ergonomics topics in Figure 3.2. Ellis and Goldberg considered 27 syllabi, similar in magnitude to the current study. For comparison, data from their survey are cited in the results and are marked “Ellis and Goldberg (1992)”.

Yet another survey on human factors education was published in 1992 by Van Cott and Huey (1992). The scope of that study was broader and more comprehensive than either Ellis and Goldberg or the present study. The authors collected responses from 971 human factors specialists and supervisors via a computer-assisted telephone interview about their professional activities and education; they also collected responses from 48 university graduate programs listed in the Directory of Human Factors Graduate Programs regarding program descriptions, courses offered, and textbooks frequently cited in the courses. For comparison, observations from their data are mentioned with the other sets of data in the results.

3.1.2 Survey results—topics

Figure 3.2 lists the topics considered for the present study. For each topic, the percentage of sampled courses that include it is indicated. All of the courses surveyed included at least one of the listed topics (a requirement of the survey).

For the 29 courses sampled, an average of 36% of “lecture-days” covered physical ergonomics. A lecture-day is defined as a day on the course schedule with mention of a particular topic for presentation—breaks, discussions, exams, and reviews are not counted as lecture-days. The courses sampled had an average of 18.8 total lecture days. For the 89% of courses covering anthropometry, 9% of lecture days included discussion of the topic (an average of 1.6 lecture-days). Several useful topics for design are listed near the bottom of Figure 3.2, including “reach, clearance, or posture”, “demographics”, and “manikins/DHM”. These topics were covered in about 10% of the courses sampled.
Figure 3.2 compares data from Ellis and Goldberg (1992), indicated in a lighter shade and labeled “Ellis and Goldberg (1992)” in the first row. Of the 14 topics identified for the current study, 7 were also identified by Ellis and Goldberg. Some topics shown in Figure 3.2 had not seen wide implementation in 1992—for instance, digital human modeling (DHM) and universal design have gained prominence in recent years in physical ergonomics. It is important to acknowledge that Ellis and Goldberg may have used different criteria for their sorting of topics. For example, they may have included “manikins” as part of “anthropometry”. Nevertheless, the data from Ellis and Goldberg provides an interesting comparison of topics over the 20-year interval between the studies.
As another comparison, Van Cott and Huey (1992) investigated these topics by interviewing human factors professionals and graduate program administrators. The interviews asked professionals if they received coverage in each of 77 topics; graduate program administrators were asked if their university requires coverage for each of the same 77 topics. Table 3.1 lists a subset of 9 topics similar to those listed in Figure 3.2 with the percentage of human factors professionals receiving education on the topics and the percentage of university programs requiring courses on the topic.

### 3.1.3 Survey results—textbooks

An examination of the syllabi reveals that 13 textbooks were used across 22 courses (7 courses had no primary text). Figure 3.3 lists textbooks used by more than one course. Ellis and Goldberg identified 11 textbooks in their study and four of the textbooks were the same as those identified by the present study. These textbooks are shown for comparison in Figure 3.3.

Van Cott and Huey (1992) asked the respondents in their study to identify any books used as reference at work. They identified the top 10 books based on the number of times

---

**Table 3.1: Physical ergonomics topic breakdown for 1992, showing percent of university programs requiring courses providing education in the indicated subjects and human factors professionals who received education in the indicated subjects (Van Cott and Huey, 1992). The 1992 data are compared with the current study which assessed courses that included the indicated topics on their syllabi.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Univariate statistics</td>
<td>83%</td>
<td>71%</td>
<td>N/A</td>
</tr>
<tr>
<td>Work station design</td>
<td>79%</td>
<td>36%</td>
<td>54%</td>
</tr>
<tr>
<td>Anthropometry</td>
<td>74%</td>
<td>31%</td>
<td>89%</td>
</tr>
<tr>
<td>Work physiology</td>
<td>70%</td>
<td>29%</td>
<td>46%</td>
</tr>
<tr>
<td>Hand tool design</td>
<td>64%</td>
<td>25%</td>
<td>32%</td>
</tr>
<tr>
<td>Multivariate statistics</td>
<td>57%</td>
<td>67%</td>
<td>N/A</td>
</tr>
<tr>
<td>Biomechanics</td>
<td>53%</td>
<td>25%</td>
<td>54%</td>
</tr>
<tr>
<td>Aging</td>
<td>20%</td>
<td>22%</td>
<td>11%</td>
</tr>
<tr>
<td>Handicapped</td>
<td>16%</td>
<td>18%</td>
<td>18%</td>
</tr>
</tbody>
</table>

---

37
cited. Many of these texts appear in Figure 3.3, including Sanders and McCormick (most frequently cited), Wickens, et al. (fifth most frequently cited), and Kodak (seventh most frequently cited).

Of interest to the current study is the treatment of anthropometry within each text. Each of the textbooks listed in Figure 3.3 have at least one section devoted to some discussion of anthropometry and its application for design. Chaffin, et al. approach design from a biomechanics perspective and the treatment of anthropometry is fundamentally different than the other texts, which present data from a more traditional applied perspective. Thus, Chaffin, et al. is not considered for analysis in this section. Bridger is also not considered, bringing the total number of textbooks for comparison to five.

Table 3.2 compares several key features of the texts under consideration. The following paragraphs summarize a few salient features from the table.

**Sources of anthropometric data**

The NASA *Anthropometric Source Book* (WebbAssociates, 1978) was most frequently recommended as a source of anthropometric data—all of the textbooks except Konz & Johnson recommend this source. Other military surveys are also frequently recommended, including White and Churchill (1971), Clauser et al. (1972), Gordon et al. (1989), and
NASA (1995). CAESAR (Robinette et al., 2002) was mentioned as an “up to date” source of civilian anthropometry in Freivalds & Niebel and Wickens, et al.

Despite the aforementioned recommendations, each of the texts presented tables of anthropometry pulled from a different source of data. Freivalds & Niebel and Sanders & McCormick present data from Kroemer (1989), which are made up of a derived data set created by developing military-based regression equations applied to civilian anthropometry. Figure 3.4 shows the table of data from the text; the use of basic line drawings and values for average, 5th, and 95th percentile male and female anthropometric measures typifies the presentation of anthropometric data in most textbooks. Military data from Kroemer et al. (1994) is displayed in Konz & Johnson. The other two texts, Kodak and Wickens, et al., present an original amalgamation of military and industrial populations created for the Kodak text.

Design techniques

Each of the texts comments on the application of anthropometric data in some fashion, but none of the texts provide in-depth discussion or application to simple problems. Some of the texts discuss the application of anthropometry in a subsequent section on workspace design—considering space requirements, clearance, reach, etc. A review of univariate statistics (e.g., percentiles, normality, etc.) appears in Freivalds & Niebel, Wickens, et al., and Konz & Johnson.

All of the texts introduce the concepts of “design for the average”, “design for extremes”, and “design for adjustability”. Sanders & McCormick and Wickens, et al. integrate a multistep process similar to the HFES 300 guidelines (HFES 300 Committee, 2004). The caveats of multivariate anthropometric design are mentioned in Konz & Johnson, Kodak, and Sanders & McCormick—such a mention usually describes the fallacy of the “percentile man” but does not provide specifics for how to consider multiple dimensions of anthropometry. Konz & Johnson cite Hudson et al. (1998) as a reference for better understanding multivariate design.

Wickens, et al., Konz & Johnson and Freivalds & Niebel mention various digital human modeling packages as tools for solving problems. A concluding remark in Kodak
notes that while the tables of physical anthropometry available today are useful for accommodating more people than not using tables, the authors conjecture that ultimate design tools of the future will be more complex.

**Population variability**

All of the texts talk at some length about variability apparent in target populations. Sex differences are mentioned in all the text and age, race/ethnicity, and occupation are cited as sources of variability in all of the texts except Freivalds & Niebel. Moreover, ability (and disability) and secular trends are each mentioned in two of the texts. Three of the texts comment on the appropriateness of military data applied to civilian populations. The authors of Kodak conclude that the U.S. military data includes many racial/ethnic subgroups and is therefore appropriate when designing for many non-U.S. populations (e.g., Europe, Africa, etc.).
Table 3.2: Comparison of several relevant features of the texts under consideration. Dots indicate mention of the resource or topic in the text. “Chapter” denotes the main section of the text discussing anthropometry and its application—the analysis was limited to this chapter. The “primary data source” denotes the source of data provided in tables. Any other general sources of anthropometry mentioned in the text are listed under “secondary data sources”. Structural/functional data or any data specialized for a particular sub-population or application are not included. The column headings “W”, “M/S”, “K/J”, “F/N”, and “K” correspond with the five texts, which are, respectively, Wickens et al. (2004), Sanders and McCormick (1993), Konz and Johnson (2004), Freivalds and Niebel (2008), and Kodak’s Ergonomic Design for People at Work (2004).

<table>
<thead>
<tr>
<th>Chapter</th>
<th>W</th>
<th>M/S</th>
<th>K/J</th>
<th>F/N</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary anthropometric data source</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kodak (1983)</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kroemer (1989)</td>
<td></td>
<td>●</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Kroemer et al. (1994)</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>Secondary anthropometric data sources</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O’Brien and Sheldon (1941)</td>
<td></td>
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<td>●</td>
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<tr>
<td>NHES I, II (1960’s-1970’s)</td>
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<td>●</td>
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<tr>
<td>White and Churchill (1971)</td>
<td></td>
<td></td>
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<td></td>
<td>●</td>
</tr>
<tr>
<td>Clauser et al. (1972)</td>
<td></td>
<td></td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NASA (1978)</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>ANSUR (1989)</td>
<td></td>
<td>●</td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Jürgens et al. (1990)</td>
<td></td>
<td></td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marras and Kim (1993)</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>NASA (1995)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Pheasant (1996)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>CEASAR (2002)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Design techniques</td>
<td></td>
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<tr>
<td>Design for average, extremes</td>
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<td>●</td>
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<td>●</td>
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<td>Sizes and adjustability</td>
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<td>●</td>
<td>●</td>
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<td>Task-based recommendations</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Univariate statistics (e.g., mean, percentiles, etc.)</td>
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<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Multivariate caveats</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Digital human modeling</td>
<td></td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User trials with mock ups</td>
<td></td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-step design procedure</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthropometry measurement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Proportionality constants</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Population variability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Age</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Race/ethnicity</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Occupation</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Military vs. civilian</td>
<td></td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>Secular</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.4: Anthropometric data table, from Freivalds and Niebel (2008). The presentation of simple line drawings of dimensions with 5\textsuperscript{th}, 50\textsuperscript{th}, and 95\textsuperscript{th} percentile values is typical of data that appear in textbooks.

<table>
<thead>
<tr>
<th>Body dimension</th>
<th>Sex</th>
<th>Dimension (in)</th>
<th>Dimension (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stature (height)</td>
<td>Male</td>
<td>63.7 68.3 72.6</td>
<td>161.8 173.6 184.4</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>58.9 63.2 67.4</td>
<td>149.5 160.5 171.3</td>
</tr>
<tr>
<td>2. Eye height</td>
<td>Male</td>
<td>59.5 63.9 68.0</td>
<td>151.1 162.4 172.7</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>54.4 58.6 62.7</td>
<td>138.3 148.9 159.3</td>
</tr>
<tr>
<td>3. Shoulder height</td>
<td>Male</td>
<td>52.1 56.2 60.0</td>
<td>132.3 142.8 152.4</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>47.7 51.6 55.9</td>
<td>121.1 131.1 141.9</td>
</tr>
<tr>
<td>4. Elbow height</td>
<td>Male</td>
<td>39.4 43.3 46.9</td>
<td>100.0 109.9 119.0</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>36.9 39.8 42.8</td>
<td>93.6 101.2 108.8</td>
</tr>
<tr>
<td>5. Knuckle height</td>
<td>Male</td>
<td>27.5 29.7 31.7</td>
<td>69.8 75.4 80.4</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>25.3 27.6 29.9</td>
<td>64.3 70.2 75.9</td>
</tr>
<tr>
<td>6. Height, sitting</td>
<td>Male</td>
<td>33.1 35.7 38.1</td>
<td>84.2 90.6 96.7</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>30.9 33.5 35.7</td>
<td>78.6 85.0 90.7</td>
</tr>
<tr>
<td>7. Eye height, sitting</td>
<td>Male</td>
<td>28.6 30.9 33.2</td>
<td>72.6 78.6 84.4</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>26.6 28.9 30.9</td>
<td>67.5 73.3 78.5</td>
</tr>
<tr>
<td>8. Elbow rest height, sitting</td>
<td>Male</td>
<td>7.5  9.6 11.6</td>
<td>19.0 24.3 29.4</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>7.1  9.2 11.1</td>
<td>18.1 23.3 28.1</td>
</tr>
<tr>
<td>9. Thigh clearance height</td>
<td>Male</td>
<td>4.5  5.7  7.0</td>
<td>11.4 14.4 17.7</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>4.2  5.4  6.9</td>
<td>10.6 13.7 17.5</td>
</tr>
<tr>
<td>10. Knee height, sitting</td>
<td>Male</td>
<td>19.4 21.4 23.3</td>
<td>49.3 54.3 59.3</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>17.8 19.6 21.5</td>
<td>45.2 49.8 54.5</td>
</tr>
<tr>
<td>11. Buttock-knee distance, sitting</td>
<td>Male</td>
<td>21.3 23.4 25.3</td>
<td>54.0 59.4 64.2</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>20.4 22.4 24.6</td>
<td>51.8 56.9 62.5</td>
</tr>
<tr>
<td>12. Popliteal height, sitting</td>
<td>Male</td>
<td>15.4 17.4 19.2</td>
<td>39.2 44.2 48.8</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>14.0 15.7 17.4</td>
<td>35.5 39.8 44.3</td>
</tr>
<tr>
<td>13. Chest depth</td>
<td>Male</td>
<td>8.4   9.5 10.9</td>
<td>21.4 24.2 27.6</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>8.4   9.5 11.7</td>
<td>21.4 24.2 29.7</td>
</tr>
<tr>
<td>14. Elbow-elbow breadth</td>
<td>Male</td>
<td>13.8  16.4 19.9</td>
<td>35.0 41.7 50.6</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>12.4  15.1 19.3</td>
<td>31.5 38.4 49.1</td>
</tr>
<tr>
<td>15. Hip breadth, sitting</td>
<td>Male</td>
<td>12.1  13.9 16.0</td>
<td>30.8 35.4 40.6</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>12.3  14.3 17.2</td>
<td>31.2 36.4 43.7</td>
</tr>
<tr>
<td>X. Weight (lb and kg)</td>
<td>Male</td>
<td>123.6 162.8 213.6</td>
<td>56.2 74.0 97.1</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>101.6 134.4 197.8</td>
<td>46.2 61.1 89.9</td>
</tr>
</tbody>
</table>

Source: Kroemer, 1989.
3.1.4 Survey discussion

As stated in the introduction of this chapter, two objectives for the syllabi and textbook surveys are to verify assertions that: (1) the scope and time spent on relevant topics in college programs covering physical ergonomics may contribute to weak understanding of how to solve problems involving anthropometry and accommodation, and (2) contemporary textbooks in broad use do not provide the tools necessary to properly account for the anthropometry of target user populations. The following paragraphs discuss how the results confirm these assertions.

Considering class time usage, it is unlikely that very many universities offer a well-rounded, applications-based approach to understanding anthropometry and its application. Anthropometry is covered in the vast majority (89%) of the undergraduate and graduate courses discussing physical ergonomics that were sampled for this study. However, anthropometry and its application is only covered on an average of 1.6 lecture-days before moving on to other topics. While a few syllabi indicated an opportunity to experiment with anthropometry (e.g., students measure each other), no syllabi made mention of comprehensive design projects involving anthropometry.

Other useful topics for design also receive only limited coverage. For instance, demographics and digital human modeling appear near the bottom of the list in Figure 3.2 and were only covered in about 10% of the courses sampled. Related topics gaining increased importance for designing products that work well for differently abled people—including designing for disabilities and universal design—were also covered in a small percentage of courses (18% and 14%, respectively). Table 3.1 indicates that many human factors practitioners did not receive education in many topics in physical ergonomics when the survey was conducted in 1992—for instance, only 31% received education in anthropometry. While several years have elapsed since that study, limited coverage of several important topics is an ongoing problem today. This finding emphasizes the need for practical and easily available tools for designing for body size and shape.

Considering the textbooks sampled, students are not provided with adequate resources to properly design for user body size and shape. Inappropriate or outdated
sources of anthropometry were cited in all of the texts. With very few exceptions, military data are not appropriate for the design of products and environments to be used by civilians because of substantially greater variability in age, fitness, and other demographic variables of civilian populations. However, many of the texts present military data for general design activities. No data were provided in the texts beyond mean and 5th/95th-percentile anthropometric values. Some texts noted that univariate percentiles are inappropriate for multivariate problems, but none described how to properly solve such problems. Limitations of univariate percentiles and the proper solution of multivariate problems were discussed in Chapter II. The absence of simple, practical examples in all of the texts is surprising—the only applications were many-dimensional workspace design problems.

To be fair, the courses and textbooks discussed in Sections 3.1.2 and 3.1.3 were not intended to be thorough resources for designing for body size and shape. The aim of this survey is not to discredit or devalue these resources—they may be quite good as a broad overview of many topics from time studies to biomechanics. However, the textbooks and courses discussed in this chapter are in many cases the only resources engineers and practitioners in human factors have been exposed to, and may be the only ones they consult for guidance when configuring products or environments to account for human variability. Unfortunately, this means that products and environments used by people are designed using inaccurate and incomplete data and methods.

There are few texts that are well-suited to the task of designing for body size and shape. Three examples of more thorough resources for designing for anthropometry are Roebuck (1995), Pheasant and Haslegrave (2006), and HFES 300 Committee (2004). Of the courses sampled, one listed the Pheasant and Haslegrave (2006) as an optional text, and two listed excerpts from the book as reading assignments. These specialized resources do a more comprehensive job of presenting the complexities of working with anthropometric data than the run-of-the-mill course texts in Figure 3.3. They discuss appropriate selection of a target population, measurement of anthropometry, running experiments, and the use of appropriate multivariate techniques. These texts could be further augmented by including principles of Design for Human Variability—namely, discussion of how
to perform quantitative simulation of anthropometry and preference to permit direct interaction for determining accommodation, cutoff limits, etc.

However, the argument may still be made that no matter how well-written a text might be, multivariate complexities in anthropometric data are difficult to convey in a textbook. Moreover, it is virtually impossible to keep a textbook current with dynamic data that represent an accurate, up-to-date snapshot of target user anthropometry. The openness and currency of the internet and the proliferation of mobile apps for accomplishing a wide array of tasks offer new opportunities for human factors education. Literature in the area of improving human factors education is discussed next.

3.2 Additional literature regarding human factors in education

Pragmatic, case-based education in human factors/ergonomics has been praised many times in the literature. Brown (1985) investigates a strategy for addressing the dearth of engineers equipped to solve challenging problems in this area and terms his approach “ergonomics by stealth”. The study found that effective learning methods are activity-based and build on students’ commonsense, experience, and skills. Liker et al. (1990), which investigated the effectiveness of short-duration lecture-based continuing education in the area of occupational physical stress analysis, largely supports this notion. Lectures were found to marginally improve factual knowledge but did little to improve skill in solving real problems. Jones (1999) explores several hands-on projects in human factors education, concluding that such activities provide a range of experiences that are valuable for the student. Greene (2006) presented other hands-on projects with a similar conclusion. Bernard (2000) found that case studies in occupational ergonomics offered beneficial first-hand experience to students. Shattuck (2001) investigated human factors (engineering psychology) students’ involvement in interdisciplinary design teams and concluded that such participation led to a better product and more thorough design experience. All of these studies offer support for the benefits of interactive, hands-on, practical education in ergonomics education.
The importance of familiarity with human factors by non-human factors professionals has also been studied in the literature. Scown (1998) explored how human factors education for accountants and resource managers would improve the product procurement process in information technology, since their decisions play a key role in the working environment of employees. Recommendations are made for including basic human factors familiarity in educational programs for administrators. Stanton and Young (2003) caution against the use of more advanced ergonomics methods by novices, but agree that simple analyses might be “given away” to novices with some training, to the ultimate benefit of a project.

Rantanen and Moroney (2011) report a survey that studied the educational and skill needs of new human factors/ergonomics professionals by sampling 52 respondents in 2011. Respondents rated how well their college education prepared them to meet their job requirements on a scale ranging from 1 (“not at all”) to 6 (“extremely well”). The study found that participants on average rated the subject of “anthropometry and demography” as 3.88 and “physical environment” as 4.22; 86% and 92% of respondents, respectively, reported that these topics are relevant to their job. In the study, a rating of 3 corresponded with “inadequately” and 4 with “adequately”. This survey indicates that respondents find these topics very relevant, but may feel that their education was barely adequate to prepare them to solve problems in these areas.

Given the evidence provided throughout this chapter, there is room for improvement in collegiate engineering education on practical design for user body size and shape. Such improvement is a significant motivator for the present work, as discussed in the Introduction. While some organizations may have the benefit of designers who are both well-trained and practical in their application of “ergonomic” or DfHV principles, poorly designed products and environments are testament that challenging design problems involving optimization of user-product interaction find their way into the hands of engineers with little or no exposure to such principles. Incorporating best-practices for designing for body size and shape into undergraduate courses in industrial, mechanical, and design engineering will lead to practicing engineers with the requisite skills to create products with improved user fit, safety, and cost.
CHAPTER IV

DESIGN PROCESS: HOW DO PRACTITIONERS APPROACH THE PROBLEM?

Chapter II reviewed available literature on anthropometry and its use for design, examining sources of data and published techniques for applying that data to optimize user-artifact interaction. The chapter also examined how these areas have changed over time and problems that have become evident with simple univariate techniques. Chapter III investigated the treatment of anthropometry in physical ergonomics education by examining 29 syllabi for courses across the United States, along with textbooks used in the classes and their coverage of anthropometry. Together, these two efforts help to paint a picture of available knowledge and resources available to designers for considering anthropometry in their designs. However, further insight may be gained by discussing these topics directly with designers themselves, and this chapter summarizes the results of a research effort to achieve this goal.

This chapter discusses a sample of designers’ knowledge of anthropometry, ergonomics/human factors, and universal design, their attitudes towards these subjects, and the tools and methods used to support design activities in these areas. For the purpose of this research, the term ‘designers’ includes professionals (e.g., engineers, designers, researchers, or analysts) practicing in industry or government research organizations doing work in some way related to ergonomics/human factors. Comments from one-on-one interviews are used as a tool to obtain an anecdotal assessment of the current state of physical ergonomics, but a semi-structured interview format also provided objective responses to specific areas of inquiry. A separate web survey asking about respondents’ design process also provides additional data for comparison. General
discussion of the survey findings and their significance is saved until after presentation of all of the results.

4.1 Conversations with designers

Two distinct populations of designers are considered. The first is a sample of eight specialists in ergonomics/human factors in the United States. The second is a broader sample of eleven professionals involved with product design, universal design, and architecture in the Republic of Ireland. While students and professors were also sampled for the Irish interviews, their responses are not included in this chapter since the focus is on feedback from designers in industry.

The Irish survey was funded in part by the Irish National Disability Authority (NDA) Centre for Excellence in Universal Design (CEUD) in an effort to better understand how body size may be considered in guidelines for universal design. Apart from the financial and logistical support offered by the Irish government, designers in Ireland constitute a valuable survey population for other reasons. The country—and particularly the city of Dublin where the interviews were conducted—is small and well-connected, making it easier to find knowledgeable participants and follow-on referrals. The country’s small size also allows designers in Ireland to quickly adapt to new approaches to design, increasing the likelihood that design recommendations would be implemented by practitioners. Moreover, the country—as well as Europe at large—is generally active in design education and policy. For instance, Ireland recently established the Centre for Excellence in Universal Design to fulfill the objectives of the Irish Disability Act 2005. Under the Act, the country has an obligation to promote design of environments and products that consider uses “by all people, regardless of their age, size or disability” (Centre for Excellence in Universal Design, 2012).

The informed consent and questions provided to participants in both surveys appear in Appendix C. Two applications were filed with the Penn State Office of Research Protections for the use of human participants for research for the U.S. and Ireland surveys (see Appendix A). Both studies were determined to be “exempt” by the Penn State IRB.
Table 4.1 at the end of Section 4.1 compares results from the two surveys. The next two sections summarize findings shown in the table; the two populations of designers are considered separately over the next two sections.

### 4.1.1 Ergonomics specialists in the U.S.

Industrial practitioners in ergonomics/human factors in the United States were identified based on personal relationships and knowledge of their work and expertise. Seven of the eight U.S. participants are ergonomics specialists. Don Norman (author of *The Design of Everyday Things* and several other books on user-centered design) was kind enough to participate as well, but is not counted in the tally of specialists. In his books, Dr. Norman comments as a theorist and advocate for user-centered design, as opposed to a nuts-and-bolts practitioner. Several of his comments during his interview are noted throughout this section, where appropriate. Dr. Norman agreed to be personally identified in the survey results.

The seven remaining specialists sampled for the survey have an average of 18 years of experience with human factors, with a range of 1 to 28 years. Six of the seven received collegiate education in human factors, either at the undergraduate or graduate level. Many of their titles include “human factors engineer” or “ergonomist.” Their employers span a range of market segments, including commercial aircraft, office furniture, commercial trucks, and the military. These represent industry hotspots in the application of body size for design. According to Dr. Norman, design for people is important in any field, but “the military and commercial aviation are probably the best fields, and then everyday computer design is next.”

**Design goal for user accommodation**

Among the specialists, the most common accommodation goal is designing for a range of body dimensions. Specifically, the industry standard “5th to 95th” is advocated by six of the seven specialists. This goal seeks to accommodate 5th-percentile to 95th-percentile dimensions in a population. One specialist lamented that their products cater to a Western population despite global sales, and noted that this is an area for improvement at their
organization. Two noted that their goals are typically set at a higher level by contract requirements or regulations. Three also noted that the goal may be project-specific, sometimes depending on the preferences of a particular client or designer.

There are two problems with the “5th to 95th” standard. First, it is unclear whether this goal makes it a priority to achieve 90% accommodation for the population, or 90% accommodation for each of several relevant dimensions. To achieve the former, an appropriate multivariate technique such as PCA or DHM, or a DfHV technique, would be required. Striving for the latter would fall into the pitfalls of the “percentile man”. Second, accommodation of 90%—or even 95%—of a population is a questionable goal. According to Dr. Norman, “There’s a feeling that you should hit the 90th/10th percentiles or maybe 95th/5th percentiles. If you’re in the military, that’s probably OK. But maybe not. If you are making a commercial product, like an automobile manufacturer, that’s not good enough. That leaves out a tremendous number of people.”

Sources of anthropometric data

The specialists identified several sources of anthropometric data that they or their coworkers use in their work. Among them, ANSUR was most commonly cited (6/7), followed by CAESAR (4/7), proprietary data (3/7), NHANES (2/7), Dreyfuss templates such as Humanscale or Measure of Man (2/7), NIOSH (1/7), and the Dutch DINED data (1/7). Three of the specialists lamented the lack of available anthropometric data representative of their target user populations.

Digital human modeling

Digital human modeling is used by five of the seven specialists. Jack was the most commonly cited program (3/7), followed by CATIA Human (2/7) and Safework (1/7). Three of the seven noted that a “cadre” of manikins were specially developed to properly account for multivariate variability—achieving fit of this cadre ensures that the desired portion of the target population will fit. Use of body scan data in CAD for virtual fitting was identified by one of the specialists. The most common use of DHM was for evaluation (4/7). One specialist also noted their usefulness for visualization and another
emphatically praised the use of “Jack cartoons” to both make design decisions and persuade management-level decision-makers.

One of the challenges of implementing digital human modeling in industry is their high cost. One of the specialists refrains from using DHM for this reason, despite the large size and profitability of their organization.

Dr. Norman offers the following insight on digital human modeling, and digital design tools in general. “I think those are absolutely the direction we must be moving. Those are essential and they are a very valuable aid. [...] If you look in every single field where these tools have been implemented, the best designers use them.”

User experiments; fit studies

All of the seven specialists make use of user experiments or fit studies in some way. Most commonly, they are used for evaluation of finished products (5/7). Other uses identified are for benchmarking (2/7), setting targets (1/7), and usability testing (1/7).

Effective decision-making evidence

A chief goal of the present work is to identify types of evidence that are useful for making decisions about human variability, product design dimensions, and accommodation. The specialists were asked directly about the types of evidence (e.g., statistical analysis, figures, DHM renderings, etc.) that they find most effective. Four of the participants noted that CAD renderings were effective, followed by statistical analysis (2/7), figures showing problem areas (2/7), lists or descriptions of dimensions that do or do not fit (1/7), user feedback (1/7), physical mockups (1/7), and expert opinion or testimony (1/7).

Major challenges

An interesting opportunity afforded by this study is the chance to ask designers about the major hurdles they encounter in their work. The range of responses was diverse. Lack of precision—or the existence of uncertainty—was communicated by two of the specialists. Other responses include the challenge of modeling and then accommodating clothing and equipment (2/7), lack of representative anthropometric data (1/7), misapplication of
anthropometric data (1/7), a lack awareness of various tools for design (1/7), limitations of DHM to model real and dynamic behavior (1/7), resource limitations such as money and time (1/7), an attitude where everyone thinks they can do it (1/7), getting human factors involved early in the design process (1/7), posturing (1/7), and the balance between accommodation and weight in the aviation sector (1/7).

Dr. Norman has a few thoughts on the challenges that plague human factors in industry. “It’s a lack of awareness. Engineers believe that they don’t need human factors. Because after all, they’re people, so they understand people. The truth is they don’t.” On the relationship between designers or business people and human factors practitioners, “I know places where they work really well as teams. In the product design field, the human factors people are respected and they’re equal partners. But in many large companies the engineers will tend to rule—or the domain experts, the chief driver or the chief pilot. And they’re very skeptical of all this stuff that comes out of books. And then that’s where, especially the people on the human side, whether it’s psychologists doing human-computer interaction or just general human factors, they’re not much well regarded because they seem unnecessary and all they do is slow us up and all they do is talk common sense anyway.”

4.1.2 Professionals in Ireland

Of the sample of eleven Irish participants presented in this section, four are architects, three are product developers or industrial designers, three are researchers, and one is a clinical engineer. These participants were identified primarily based on personal contacts within the Irish Centre for Excellence in Universal Design (CEUD). They were selected to represent a cross-section of end-users of practical guidelines for considering user size for universal design. Not all participants were experts in designing for people or body size, but all of them had at least some familiarity with the field. The participants had an average of 10 years of experience in their current area of practice, with a range of 4 to 20 years. Five received dedicated education on human factors as part of the undergraduate or graduate education. The same set of six topics from the previous section are addressed in this section. Since one of the NDA’s primary purposes for the study is to integrate
size considerations with universal design, an additional question is presented here as compared with the previous section, “why strive for universal design?”

**Design goal**

Participants were asked what their goal would be when striving to physically accommodate users in the design of a product. The range of responses was broad and included: design for as many as possible (2/11), custom design for specific users (2/11), design requirements change by project or application (2/11), design for extremes (2/11), design for standards (1/11), design for the limiting user (1/11), and design for the mean (1/11). The responses from this sample show a greater level of abstraction when compared with the sample of U.S. ergonomics specialists. This is to be expected, as there are no ergonomics specialists in the Irish sample group and design is approached from a broader perspective.

**Sources of anthropometric data**

Data sources referenced by the participants were highly sensitive to their occupation. Among the architects, the *New Metric Handbook* (3/4) and *Neufert’s Architects’ Data* (3/4) were most commonly cited. Both of these resources include templates and several average dimensions or ranges of dimensions. Two architects cited other design manuals or handbooks, and one recommended averages. Among the remaining participants, responses included proprietary or custom measurements (6/7), standards (3/7), Dreyfuss templates such as *Humanscale* or *Measure of Man* (2/7), data is hard to find (2/7), AdultDATA (1/7), and the Dutch DINED data (1/7).

**Digital human modeling**

Among participants, eight claimed the use of human models in some sort of CAD package. Five DHM programs were listed by three participants—Jack (1/11), Mannequin (1/11), RAMSIS (1/11), AnyBody (1/11), and VICON (1/11). The use of libraries of human figure mockups in AutoCAD were mentioned by three of the participants, who were all architects. Another participant listed the crash-test simulator MADYMO. Human
modeling was used for: evaluation (3/11), rendering or presentation (3/11), design (2/11), and simulation of impairment (1/11).

User experiments

All of the eleven participants claimed the use of experiments or user evaluations in their work. Most commonly, they are used for benchmarking or identification of issues (6/11), evaluation or trial configurations (4/11), design (3/11), and to identify improvements (1/11).

Effective decision-making evidence

Among the types of effective representations or evidence for making decisions, participants identified the following: figures or illustrations (3/11), user or stakeholder feedback (3/11), CAD figures (2/11), description of what fits or does not fit (2/11), anecdotal or visual evidence of user struggles (2/11), literature or data references (1/11), and physical mockups (1/11).

Major challenges

Several challenges were identified by participants. These include: trading off various measures of performance or satisfying conflicting goals (3/11), accommodating changing user requirements such as disabilities, strollers and increasing physical size (3/11), awareness of issues in designing for users (2/11), limitations on time or money to solve problems (2/11), availability and reliability of body size data (2/11), evaluating performance (2/11), lacking or insufficient software tools and human models (1/11), and overcoming users’ visual perception of comfort to achieve actual comfort (1/11).

Why universal design?

All of the participants claimed familiarity and interest in universal design. An interesting question is, why? When asked this open-ended question, a few common responses emerged. Responses included that it is mutually beneficial for businesses and consumers (4/11), universal design is the “right thing to do” (3/11), it is good sense or a best practice (2/11), it will make the world a better place and yield more usable products
and environments (2/11), there is a legal imperative (1/11), it should be a natural part of design without being separately considered (1/11), it gives the designer a cover-all approach to usability (1/11), an aging population necessitates universal design (1/11), and it tailors designs to the tails of the population bell curve (1/11).

Table 4.1: Comparison of responses for the U.S. specialists and Irish practitioners. The total number of participants indicating each response is shown. Results are sorted first by the frequency of U.S. specialist responses, then by frequency of Irish practitioner responses.

<table>
<thead>
<tr>
<th>Source of anthropometric data</th>
<th>U.S. specialists</th>
<th>Irish practitioners</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total number of participants</strong></td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td><strong>Design goal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5th to 95th percentile accommodation</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Specific to project or client</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Contracts, regulations, or standards</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>As many as possible</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Custom design</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Design for extremes</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Design for the limiting user</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Design for the mean</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Sources of anthropometric data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANSUR</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>CAESAR</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Proprietary data; custom measurements</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Dreyfuss templates</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>NHANES</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>NIOSH</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Dutch DINED</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><em>New Metric Handbook</em> (Adler, 2000)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><em>Architects' Data</em> (Neufert et al., 2008)</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Standards or manuals</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Hard to find data</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>AdultDATA (Peebles and Norris, 1998)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Digital human modeling</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jack</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>CATIA Human</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Safework</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>CAD (Solidworks, AutoCAD)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Mannequin</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>RAMSIS</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AnyBody</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>MADYMO</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>VICON</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

*Continued on next page*
Table 4.1: Comparison of responses for the U.S. specialists and Irish practitioners. The total number of participants indicating each response is shown. Results are sorted first by the frequency of U.S. specialist responses, then by frequency of Irish practitioner responses.

<table>
<thead>
<tr>
<th>User experiments; fit studies</th>
<th>U.S. specialists</th>
<th>Irish practitioners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluation</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Benchmarking</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Setting targets</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Usability testing</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Identify improvement</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Effective decision-making evidence                 |                   |                     |
| CAD                                                | 4                | 2                   |
| Figures, illustrations (e.g., showing problem areas)| 2                | 3                   |
| Statistical analysis                               | 2                |                     |
| Expert opinion or testimony                        | 1                |                     |
| User feedback                                      | 1                | 3                   |
| Description of dimensions that do not fit          | 1                | 2                   |
| Physical mockups                                   | 1                | 1                   |
| Anecdotal or visual evidence of user struggles     | 2                |                     |
| Literature or data                                 | 1                |                     |

| Major challenges                                   |                   |                     |
| Ambiguity; lack of precision                       | 2                |                     |
| Accommodating clothing and equipment               | 2                |                     |
| Attitude; “anyone can do it”                       | 1                |                     |
| Early involvement of human factors                 | 1                |                     |
| Posturing of manikins                              | 1                |                     |
| Misapplication of data                             | 1                |                     |
| Performance tradeoff (e.g., accommodation vs. cost)| 1                | 3                   |
| Limitations on time and money                      | 1                | 2                   |
| Availability and reliability of representative data| 1                | 2                   |
| Awareness of design tools, methods, and considerations| 1               | 2                   |
| Limitations of DHM, software tools                 | 1                | 1                   |
| Accommodating changing requirements (e.g., obesity)| 3                |                     |
| Evaluating performance                             | 2                |                     |
| Overcoming perceived vs. actual comfort            | 1                |                     |

| Why universal design?                              |                   |                     |
| Economic imperative; mutually beneficial           | 4                |                     |
| Moral imperative; the right thing to do            | 3                |                     |
| Good sense; best practice                          | 2                |                     |
| It will make the world better, more usable, and sustainable| 2       |                     |
| Legal imperative; government guidelines            | 1                |                     |
| It should simply be a natural part of design       | 1                |                     |
| It gives the designer a cover-all approach to usability | 1           |                     |
| Population aging; healthcare demands               | 1                |                     |
| Tailors to the tails of the population bell curve  | 1                |                     |
4.2 Web survey on design process

In addition to the one-on-one interviews with designers and human factors practitioners, another effort to assess the design process of design practitioners made use of an online survey. 94 participants responded to the invitation to take part in the survey and completed some of the survey, and 83 participants finished the survey. Potential participants were identified based on their involvement in human factors/ergonomics (HF/E) at the student or professional level. The study was offered for extra credit to 48 students in IE-327 (Introduction to Work Design) at Penn State and was circulated to 85 employees at the Army Research Lab’s Human Research and Engineering Directorate. The study was also advertised to the mailing list of the Penn State Chapter of the Human Factors and Ergonomics Society and an ergonomics-related LinkedIn discussion group. The study received approval from an appropriately constituted internal review board at The Pennsylvania State University.

The web survey has five parts: (1) demographics and background assessment, (2) design process assessment, (3) use of glyph representations for design, (4) comprehension of various representations for design, and (5) preference for various types of plots for design. Parts 3-5 are covered in Section 6.2 of Chapter VI. This section addresses the first and second parts.

4.2.1 Web survey demographics, background, and experience

Figure 4.1 summarizes the demographics of respondents to the web survey, including age, experience with human factors, education in human factors, and current occupation. The figure indicates a mix of respondents on the different metrics. 50 respondents were between the ages of 18-25, and 43 respondents were older than 25. The overwhelming majority of respondents were from North America, but 3 replied from western Europe, 2 from east Asia, 1 from south Asia, and 1 from northern or central Africa (not shown

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1LinkedIn group: Dassault Systemes Virtual Ergonomics, http://www.linkedin.com/groups?gid=1792209
in Figure 4.1). A majority of respondents were students (50), but 44 respondents were non-students (i.e., professionals). Among non-students, the greatest number received training on the job (33) as compared with undergraduate education (18), graduate education (19), continuing education (14), or self-taught or no training (16).

Participants were asked to rate their acquaintance with six topics relevant to designing for body size. The six topics were: anthropometry, tables, boundary manikins, digital human models (e.g., Jack, CATIA Human), population models (i.e., experiments with regression-based models), and standards (e.g., Americans with Disabilities Act, ISO Guide 71, U.S. Military Standard 1472—Human engineering). Participants were forced to use a three-point scale of “no experience”, “familiarity”, or “expertise” and could select only
one option. “Familiarity” was defined as having heard of or implemented the topic a few times. “Expertise” was defined as having implemented the topic many times.

Table 4.2 summarizes the acquaintance of participants on the six topics for all participants and non-students. As expected, for most topics, a majority claim familiarity, and a greater portion of non-students claim expertise on a variety of topics. Notably, 93% and 89% of non-students claim either familiarity or expertise with anthropometry and tables, respectively. Non-students were more familiar with DHM, boundary manikins, and standards than both students and non-students combined.

Table 4.2: Summary of participants' acquaintance with various topics in designing for body size and shape. Familiarity is defined as having heard of or implemented the topic a few times, whereas expertise is defined as having implemented the topic many times. Percentage of respondents selecting each answer is indicated.

<table>
<thead>
<tr>
<th></th>
<th>All participants</th>
<th>Non-students</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>None</td>
<td>Familiarity</td>
</tr>
<tr>
<td>Anthropometry</td>
<td>16%</td>
<td>57%</td>
</tr>
<tr>
<td>Tables</td>
<td>19%</td>
<td>51%</td>
</tr>
<tr>
<td>Boundary manikins</td>
<td>49%</td>
<td>37%</td>
</tr>
<tr>
<td>DHM</td>
<td>34%</td>
<td>59%</td>
</tr>
<tr>
<td>Population models</td>
<td>44%</td>
<td>41%</td>
</tr>
<tr>
<td>Standards</td>
<td>33%</td>
<td>46%</td>
</tr>
</tbody>
</table>

4.2.2 Web survey design process

Table 4.3: Summary of participants' top-rated criteria when designing products intended for use by people. Percentage of respondents selecting each criteria is indicated.

<table>
<thead>
<tr>
<th></th>
<th>All participants</th>
<th>Non-students</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First</td>
<td>Within Top 3</td>
</tr>
<tr>
<td>Cost</td>
<td>12%</td>
<td>60%</td>
</tr>
<tr>
<td>Comfort</td>
<td>28%</td>
<td>64%</td>
</tr>
<tr>
<td>Physical size and weight</td>
<td>5%</td>
<td>15%</td>
</tr>
<tr>
<td>User safety</td>
<td>25%</td>
<td>52%</td>
</tr>
<tr>
<td>Product aesthetics</td>
<td>2%</td>
<td>14%</td>
</tr>
<tr>
<td>Ergonomic design</td>
<td>10%</td>
<td>53%</td>
</tr>
<tr>
<td>Durability</td>
<td>4%</td>
<td>29%</td>
</tr>
<tr>
<td>Features</td>
<td>2%</td>
<td>7%</td>
</tr>
</tbody>
</table>
To assess respondents’ design process, participants were first asked to rate their top three design criteria. The available criteria were: cost, user comfort, physical size and weight, user safety, product attractiveness or aesthetics, ‘ergonomic design’, durability, and features (e.g., material choice). Participants were asked to select the top criteria in order of importance, with 1 being the most important criteria and 3 being the third most important criteria. Participants could only choose one criteria for each rating 1 through 3.

Table 4.3 summarizes the rankings for top rated criteria for all participants and non-students. Comfort is rated highly with participants (64% of all participants place it in their top three criteria), followed by cost, user safety, and ergonomic design. Note that responses by non-students may be assumed to reflect their actual design criteria, whereas responses from students likely represent a hypothetical or ideal set of criteria.

Table 4.4: Summary of participants’ top-rated strategies when designing products intended for use by people. Percentage of respondents selecting each strategy is indicated.

<table>
<thead>
<tr>
<th>All participants</th>
<th>Non-students</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First</td>
</tr>
<tr>
<td>Tables</td>
<td>19%</td>
</tr>
<tr>
<td>Templates</td>
<td>1%</td>
</tr>
<tr>
<td>DHM</td>
<td>18%</td>
</tr>
<tr>
<td>Experiments</td>
<td>34%</td>
</tr>
<tr>
<td>Standards</td>
<td>19%</td>
</tr>
<tr>
<td>Proprietary strategies</td>
<td>5%</td>
</tr>
</tbody>
</table>

Next, participants were asked to rate their top three design strategies for solving problems involving user variability in size. The available criteria were: tables of anthropometry, two dimensional human figures (e.g., paper templates, “Measure of Man”, “Humanscale”), digital human models (e.g., Jack, CATIA Human), experiments with a sample of users and a prototype of a product, standards or guidelines for human factors design (e.g., ADA, U.S. Military Standard 1472, BIFMA, HFES 300, ISO Guide 71, ISO 6385), and proprietary strategies (e.g., guidelines or procedures in place at their organization). Participants were asked to select their top strategies in order of importance, with 1 being the most important criteria and 3 being the third most important criteria. Participants could only choose one strategy for each rating 1 through 3.
Table 4.4 summarizes the rankings for top rated strategies for all participants and non-students. Experiments were a highly favored strategy overall. Templates were less likely to be used by non-students, whereas standards were more likely to be used by non-students. DHM was likely to be used by non-students. Note that responses by non-students may be assumed to reflect their actual design strategies, whereas responses from students likely represent a hypothetical or ideal set of strategies.

Finally, participants were asked to respond to four multiple choice questions regarding design strategies for solving problems involving user variability in size. The four questions are shown in Table 4.5. The first question assesses the participants’ primary design goal. The second question assesses how the participant approaches designing for disabilities/universal design. The third question assesses sources of anthropometry the participant would be most likely to use for design. The fourth question returns to the participant’s design goal, or preferred strategy for dealing with anthropometry.

Table 4.5 summarizes the rankings for top rated strategies for all participants and non-students. For Question 1, nearly three-quarters of respondents indicated that they would design for a percentage of the population. A surprising percentage indicated that they would design for the mean (11%), although this percentage was nearly 0 for non-students. For Question 2, participants were generally evenly split in their approach for accommodating users with disabilities. Slightly more participants indicated a “separate but equal” approach (38%). For Question 3, most users indicated they would select a proprietary survey of data to represent target users (34%). It is unclear if participants intended this to mean that they would ideally prefer anthropometry representative of their target users, or if they would only use proprietary data at the exclusion of the other sources. A relatively large percentage of respondents (18%) selected “tables from textbooks”, even though other options were presented. For Question 4, respondents’ answers generally agree with Question 1, but this question reveals how participants’ would approach designing for a target percentage. A sizable portion of respondents (34%) would be likely to add an extra margin to estimates of accommodation to ensure some robustness to uncertainty in their solution.
Table 4.5: Four questions assessing respondents’ design process. Percentage of respondents selecting each answer is indicated. Each question was multiple choice and participants could select only one answer.

<table>
<thead>
<tr>
<th></th>
<th>All participants</th>
<th>Non-students</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Which one of the following goals would you most likely seek to attain?</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (e.g., average user)</td>
<td>11%</td>
<td>2%</td>
</tr>
<tr>
<td>Extremes (e.g., very smallest and largest user)</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td>Percentage (e.g., 90% of population)</td>
<td>71%</td>
<td>74%</td>
</tr>
<tr>
<td>Other</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td><strong>2 How would you prefer to account for users with disabilities?</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Same for all</td>
<td>33%</td>
<td>30%</td>
</tr>
<tr>
<td>Separate but equal</td>
<td>38%</td>
<td>36%</td>
</tr>
<tr>
<td>Custom for disabled individual</td>
<td>21%</td>
<td>24%</td>
</tr>
<tr>
<td>Other</td>
<td>3%</td>
<td>6%</td>
</tr>
<tr>
<td><strong>3 Which source of data would you be most likely to select to represent users?</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tables from textbooks</td>
<td>18%</td>
<td>16%</td>
</tr>
<tr>
<td>Online, civilian data (e.g., CDC/NHANES)</td>
<td>29%</td>
<td>16%</td>
</tr>
<tr>
<td>Online, military data (e.g., U.S. Army/ANSUR)</td>
<td>12%</td>
<td>18%</td>
</tr>
<tr>
<td>Proprietary survey</td>
<td>34%</td>
<td>40%</td>
</tr>
<tr>
<td>Other</td>
<td>4%</td>
<td>8%</td>
</tr>
<tr>
<td><strong>4 How would you select the range of anthropometry to be included in a design?</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entire population</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Design target (e.g., 90%)</td>
<td>44%</td>
<td>52%</td>
</tr>
<tr>
<td>Design target plus a margin (e.g., 92%)</td>
<td>34%</td>
<td>30%</td>
</tr>
<tr>
<td>Average Users</td>
<td>11%</td>
<td>6%</td>
</tr>
<tr>
<td>Other</td>
<td>5%</td>
<td>10%</td>
</tr>
</tbody>
</table>

4.3 Discussion and implications

The three parts of the assessment of practitioners’ approach to considering body size for design—interviews in U.S., interviews in Ireland, and a web survey—all ask similar questions, albeit in different formats with very different respondent populations. A particularly instructive activity is to identify common or unique responses across the three surveys.

Design goals for ergonomics specialists differed greatly from the broader group of Irish design practitioners. While the specialists mainly utilized the standard target of “5th to 95th” percentile accommodation, goals for the Irish practitioners could generally be described as inclusive of as many people as possible. This perhaps reflects a difference
in design philosophy that parallels the difference between “ergonomics” and “universal design” discussed in Section 2.5.2. The web survey indicated that a majority (71%) would seek to accommodate a percentage of users, but an alarming 11% of respondents would try to design for the average user. Continued education about the pitfalls of this approach is warranted.

In terms of anthropometric data sources, ANSUR is commonly used in the United States by specialists, but was not identified as a source of data by the practitioners in Ireland. One commonality between the specialists and Irish practitioners is the occasional use of the Dreyfuss templates. Despite important limitations on their use (e.g., representativeness of the data and the fallacy of the “percentile man”) they remain a valued resource. Multiple Irish respondents noted that such templates are a “tried and true” reference that all designers are expected to be familiar with. Future efforts might investigate how the limitations of templates could be mitigated to produce truly useful templates for design. The Dutch DINED data was mentioned by at least one practitioner in both groups—its use might be attributable to its unique, interactive interface (Technical University of Delft, Industrial Design, 2012). Intriguingly, the web survey found that proprietary data was most favored by respondents, followed by online, civilian data.

Practitioners in both groups make use of CAD or digital human modeling to some degree. For specialists, Jack was most commonly referenced. For Irish practitioners, human figure libraries in AutoCAD were most commonly referenced, along with a few specialized DHM programs. For both groups, DHM is most commonly used for evaluation of designs. Despite the advantages of DHM, high cost remains a barrier for its widespread use. Free, downloadable manikins would likely be a valuable resource for many designers. In the web survey, DHM was a frequent first choice among non-students, but a less frequent choice among all participants. Its specialized use in industry and lack of awareness among students are likely explanations for this difference (34% of all participants claimed no knowledge of DHM, and only 21% claimed expertise).

One overwhelming commonality among the survey groups is the consistent use of user experiments or fitting trials for design and evaluation. Some respondents emphatically replied that they use such experiments all the time and they are invaluable...
for improving user-device interaction. This is an encouraging result—experiments with real users are a useful technique for capturing otherwise unquantifiable variability in a target population and are one of the fundamentals of the Design for Human Variability best practices. Experiments were also a top-rated strategy in the web survey results.

There was not a consensus among respondents regarding effective evidence for making decisions about user accommodation in design. CAD or DHM renderings tended to be most commonly mentioned as a useful tool for communicating device performance/accommodation (4/7 specialists and 2/11 Irish practitioners mentioned these tools). Anecdotal feedback and descriptions of dimensions that fit or do not fit were also mentioned multiple times as useful evidence for decision making. Unexpectedly, expert testimony and available literature were also mentioned by some respondents as being useful evidence to present to clients or superiors.

Finally, among the greatest challenges identified by respondents, awareness of principles and tools for design was cited by respondents in both groups. A lack of representative and reliable anthropometric data was also mentioned multiple times. One Irish practitioner said they were overwhelmed by available resources and had difficulty distinguishing good data from bad. Some indication of reliability or appropriateness for a given population of users might help online anthropometric data to be used in practice.

The responses of the U.S. and Irish practitioners are instructive for understanding how practical tools may be developed and subsequently adopted by designers. Availability of representative data was identified as a key issue, along with awareness of guidelines or tools, and availability of better and/or free tools for analyzing and applying anthropometry. Results from these surveys also show that education on the pitfalls of templates and general awareness of ergonomics principles should be promoted.

The next chapter investigates improved representations of human variability that may be implemented in practical tools and guidelines for design.
Chapter II discussed background in the application of anthropometry to the design of products and environments for people. Specific challenges for designing for human variability were listed in Section 2.6.2. Three challenges identified are “preference uncertainty”, “considering multiple spaces”, and “balancing conflicting objectives”. The author’s previous research has largely focused on addressing the first challenge. Some research has also addressed the second challenge of considering multiple spaces—namely the “anthropometry” and “design” spaces. More broadly, however, there exists a need for intuitive and insightful visualizations of anthropometry, design dimensions of the product or environment, and the interplay between the two. This chapter covers various visualization techniques that may be applied to design problems involving body size and shape.

Because designing for human variability considers many dimensions simultaneously, problems in DfHV may be considered to have multidimensional multivariate (MDMV) data. There are many ways of visualizing such datasets, and this cross-disciplinary topic has been rigorously researched over the past decade or two. For instance, Dos Santos and Brodlie (2004) investigate interactive multidimensional, multivariate data visualization through data-reduction filters and small multiple arrays. Pao and Meng (1998) investigate the understanding of multivariate data in terms of a system of knowing relationships among data and holding this knowledge in a convenient, accessible form. Augmented reality has also been shown to be useful for interactive MDMV visualization (Meiguins et al., 2006). Kocherlakota and Healey (2009) present a
framework for summarizing and compressing very large datasets to highlight parts of the data that are of interest using visualization techniques such as parallel coordinates, radial visualization, spatial arrangement, and nodes, rather than simply encoding an increasing number of dimensions with such techniques. That work considers weather and meteorological data as an application. Such studies represent new and innovative techniques for multidimensional multivariate data visualization.

Agrawal et al. (2004) summarizes a three-category classification scheme for multidimensional multivariate data visualization techniques: (1) 2-variate and multiple views of 2-variate displays (e.g., fitted curves, reference grids, or small multiples), (2) multivariate displays (e.g., scatter matrices, dimensional stacking, or parallel coordinates), and (3) the use of time as an animation parameter. Representations in this chapter belong primarily to the first category, 2-variate and multiple views of 2-variate displays. Additionally, interactivity is suggested as a mechanism for interacting with the data, which is similar in some regards to the third category, using time as an animation parameter. Instead of fixing an animation in time, interactivity allows a designer to set their own timeline by exploring the consequences of changing parameters in real time.

The following types of representations are considered in this chapter for application to DfHV visualization: encoded scatter plots, density/contour graphs, and representations using humanoid glyphs. The following arrangements of these figures are also considered: interactivity, “pairing”, and “small multiples”. Each of these areas are discussed over the next several sections and experimentally evaluated in Chapter VI. The author’s previous work led to the application of many of these plots to represent human variability—such usage is not considered elsewhere in the literature. As such, Figures 5.1, 5.2, 5.3, and 5.5 are original creations.

5.1 Types of representations

5.1.1 Encoded scatter plots

Scatter plots and relational graphs (i.e., a graph wherein a dependent measure is plotted against an independent one) date back to at least 1765 (Tufte, 1992). They are among
the most basic and ubiquitous of scientific graphics. This section briefly discusses the encoding of accommodation onto basic scatter plots in the anthropometry and design spaces.

Analyzing accommodation using a two-space (i.e., anthropometry and design) architecture was introduced in Garneau (2009). Figure 5.1 shows the anthropometry and design spaces for a one-dimensional problem with a 25-member virtual population. The binary performance metric, accommodation, is encoded in both plots by coloring each virtual person blue or orange, indicating accommodation or disaccommodation, respectively. Figure 5.2 shows the anthropometry and design spaces for a two-dimensional problem, where the utility of this scheme becomes evident. While the information shown in Figure 5.1 may have been combined into one two-dimensional representation, the data in Figure 5.2 could not. Even for large-dimensional design problems, a simplification using one or two dimensions (e.g., stature and/or BMI) facilitates effective exploration of the anthropometry space and its influence on design parameters. As a preliminary tool, the two-dimensional space gives designers an intuitive feel of the sizes of people that fit and those that do not fit.
5.1.2 Density/contour graphs

Another simple relational representation is the density contour. Such graphs may be thought of as a three-dimensional histogram where areas with greater frequency of data are colored darker shades. Figure 5.3a illustrates a density contour in anthropometry space, indicating the greatest concentration of data near the mean of the two anthropometric variables. One disadvantage of using density contours as compared with scatter plots is the difficulty with encoding accommodation. Figure 5.3b represents one possibility for indicating accommodation that highlights regions in the anthropometry space where accommodation is more likely.

5.1.3 Glyphs

Glyphs are a popular type of multivariate representation wherein individual dimensions of a data point are mapped to attributes of a shape or symbol. Many types of glyphs have been developed in recent decades including, among many others, profiles (histograms), stars, trees, arrows, polygons, and faces (sometimes called Chernoff faces). It useful to think about the construction of glyphs in terms of their geometric attributes and appearance attributes (Ward, 2002). Color-coded scatter plots like Figure 5.2 employ
Figure 5.3: Probability of accommodation plotted in the anthropometry space of Figure 5.2a. On the left, darker shades indicate a greater concentration of people. On the right, darker shades indicate greater concentration of accommodated people.

Figure 5.4: Examples of “Chernoff faces” with parameters such as head, mouth, and eye size and shape encoded with different values. The figure was created with the “faces2” function in the R statistical computing software environment.

a glyph with a color attribute that indicates accommodation. Several limitations of glyphs that ought to be considered in their design include: small dataset visualization capacity due to occlusions; qualitative—not quantitative—visualization capability; and perception-based, proximity-based, and grouping-based biases in glyph mappings (Chen et al., 2008). Ward also suggests that glyphs have been insufficiently studied, and there exist many avenues for further research including new glyph designs, mechanisms to explore large datasets, and evaluation of proposed glyphs.

Given the many types of available glyphs, a natural question arises of which one to choose to illustrate a particular multivariate data set. Herman Chernoff conjectured that
a natural choice for a glyph is one that capitalizes on features of the face, since “people grow up studying and reacting to faces all of the time” (Chernoff, 1973). See Figure 5.4 for an example. He asserts that face-glyphs are primarily useful for filtering and grouping important features of data on a macro scale and that minor differences may go unnoticed without impeding the usefulness of the glyph. He also asserts that face-glyphs have little usefulness as a communication device, their primary purpose being cluster analysis, discrimination analysis, and so on for the researcher. It should be emphasized, as Chernoff asserted, that glyphs are most useful in a comparative sense, rather than an absolute sense in which the actual dimensions of glyphs are meaningful.

Some have questioned the efficacy of faces as a glyph for information sorting and analysis. Saxena and Navaneetham (1993) investigate the use of Chernoff faces as a tool for multivariate cluster analysis. They concluded that faces are less effective for recovering true cluster structure compared with non-graphical methods, but are more useful for gaining insight into the data structure. Morris et al. (2000) critique the use of face-glyphs by investigating whether they are pre-attentive, that is, whether the mind is able to automatically process salient features subconsciously. Their experimental study found that users do not process the face-glyphs pre-attentively, and therefore faces do not have advantages over other types of glyphs.

Siirtola (2005) investigated whether data-related glyphs are better than non-data-related glyphs for information processing, with the conclusion being the affirmative. The experimental study found that when users were asked to discover important relationships in a dataset about cars, accuracy increased when using car-glyphs instead of face-glyphs. Furthermore, participants found it easier to bind variable quantities to the features of cars instead of faces with the primary conclusion being that it is advantageous to match a glyph to the data, although the match need not be exact (Siirtola, 2005).

Ropinski et al. (2011) investigate usage of glyphs within the medical domain, where time and thus efficiency are a premium concern. They separate glyph properties into those supporting pre-attentive and attentive processing, with a focus on features for the pre-attentive. Significant among six recommendations for the use of glyphs in medical imaging is the fourth: “glyph visualizations should support quantitative analysis in the
attentive phase.” As first asserted by Chernoff, Ropinski, et al. confirm that a primary use of glyphs is for aggregative analysis. However, if glyphs do not capitalize on pre-attentive processing, they should also be useful for quantifying features of the data (e.g., by use of a legend). Yost and North (2005) attempt to discern whether it is preferable to use one complex figure with glyphs or multiple simple figures with glyphs, surmising that multiple views are safer. Furthermore, they argue that visual encoding is the most important feature, and that the most perceptually salient feature(s) should be used.

Beyond the faces proposed by Chernoff, anthropomorphic glyphs have been used as a visualization technique for problem solving in digital human modeling (DHM), a prominent field of study in human factors/ergonomics. Digital human models are complex representations of the size, form, and capabilities of human users of products and environments. The human figures in DHM are commonly referred to as “manikins”. DHM tools are widely used for many applications, including, for example, industrial product design (Demirel and Duffy, 2007), military aircraft design and evaluation (Kennedy et al., 2004), and assessment of wheelchair-accessible environments (Quick et al., 2005). Figure 2.8 shows a promotional screenshot for the software package Jack being used for an aircraft maintenance assessment task Siemens PLM Software (2012).

Horvath et al. (2005) review many types of DHM and stratify available tools into several categories based on the information included in the tool: morphological, material, structural, mechanical, physiological, and behavioral. While many DHM packages incorporate physiological and behavioral modeling components, the morphological
(shape) and structural (anthropometry) components are most useful for evaluating and visualizing spatial requirements of products and environments for users.

DHM manikins are essentially advanced glyphs that encode very many human-related variables (e.g., 103 dimensions in DELMIA Human (Dassault Systemes, 2012)). A primary difference between digital human models and traditional glyphs is that the manikins have only been positioned within the physical environment—for instance, the manikin in Figure 2.8 is placed within an aircraft’s three-dimensional space to evaluate clearance or performance requirements.

Traditionally, human models have not been encoded and embedded in multidimensional graphs to evaluate user performance apart from physical dimensions. Similarly, face-glyphs have been used for data analysis in other fields, but no studies employing face-glyphs for human factors analysis were found while reviewing available literature. While anthropomorphic characteristics of face-glyphs are not meaningful for most applications, a representation of the human form that varies on one or more parameters may be useful when the subject of analysis is human variability. This usage is featured in Section 6.2, where such representations are termed “human-glyphs” or “humanoid glyphs”. Another novel use of human figure models appears in Figure 5.5, in which Jack figures have been color-coded to show accommodation.

5.2 Arrangements of representations

5.2.1 Interactivity

Interactivity is a useful means for exploring data. For problems involving human variability, allowing a designer to select ranges of anthropometry to be accommodated and see the impact on ranges of device dimensions, or conversely, select ranges of a device parameter to be considered and see the impact on anthropometry would be a useful implementation. As a particularly relevant example, a project from The Delft University of Technology provides an interactive, web-based front-end for the Dutch DINED anthropometric database (Technical University of Delft, Industrial Design, 2012). The interface permits a user to select from several available target user populations, pick
relevant anthropometric measures, and then retrieve percentile values for those measures. The tool does not permit the exploration or download of raw data, however.

Interactivity has been explored for optimization in other work, notably in the *trade space visualization* or *design by shopping* paradigm (Balling, 1999; Stump et al., 2003; Yukish et al., 2007), which offers an insightful perspective that is useful for the present research.

The trade space visualization technique allows designers to input parameters, objective functions, and constraints, sample the design space, and then view the performance space with a variety of representations that facilitate comparisons. The efforts of this research have been consolidated into the Advanced Trade Space Visualizer, or ATSV, software environment. Several visualization techniques are employed in ATSV, including scatter matrices, glyph plots, parallel coordinates, dimensional stacking, and reduction of dimensions (Stump et al., 2003).

The ATSV package also has capabilities for designing under uncertainty, finding interesting features within trade spaces, displaying derivative information about selected points in the trade space, and using visual steering commands for discovery of optimal points or regions in trade space (Stump et al., 2004, 2007). The last capability is particularly important for making the environment interactive and bringing human-in-the-loop functionality to the optimization. It was shown in Carlsen et al. (2009) that visual steering commands may provide a 4-fold to 7-fold increase in the number of Pareto-optimal solutions obtained.

Wolf et al. (2009) investigated the effect of user experience on decision-making with the ATSV tool, particularly via the visual steering capability. The study found significant differences between novice and expert users, with novices unable to use visual steering advantageously to achieve better results. The research also found novices to be largely ineffective at using multidimensional data visualization tools in general. Experts were better able to utilize the tools to achieve high performance.

The trade space visualization paradigm has implications for the present research. A similar strategy is useful for visualizing DfHV problems—interactivity among different spaces and real-time exploration of optimality are key similarities. Unlike the ATSV effort, the primary outcome of the present research is not a specific tool or software environment,
although this is a secondary outcome. Instead, the primary outcome of the current work is a set of recommendations or principles for effective design based on the best principles and user experiments with particular implementations of the principles.

5.2.2 Pairing

In the introduction of this chapter, “multiple views of 2-variate displays” are described as one category of multidimensional multivariate data visualization techniques. In this work, combinations of two representations are used and referred to as “pairing”. Wickens et al. (2004) provide several useful principles to consider when designing such displays. Three particularly relevant principles to consider are:

- **Minimize information access cost.** Displays should be easily accessible and easy to find so that the cost in time or effort to move selective attention from one to another is minimized.

- **Proximity compatibility principle.** When two or more sources of information related to the same task have to be mentally integrated, attention must be divided between the two sources to complete the one task. Therefore, the two sources should have close mental proximity, which includes not only spatial closeness but also common colors, patterns, or links.
• Principle of consistency. Any displays that a user is perceiving concurrently should be consistent. For instance, color coding or organization should be the same across the multiple displays.

A common representation when describing human variability is the histogram and associated probability density function (pdf). For instance, the pdf in Figure 5.6 shows the distribution of stature for males and females in a population. A paired representation might combine this figure with another figure, such as one of the scatter plots of Figure 5.2.

5.2.3 Small multiples

Edward Tufte has published several books on the subject of effective quantitative communication of multivariate data (e.g., Tufte, 1992, 1997). While much of his work is a showcase of effective and ineffective techniques for graphing data and an accompanying narrative laying guidelines for clean design, he has also advanced new constructs useful for multivariate visualization. In Tufte (1992), small multiples are discussed, which are a series of graphs showing the same combination of variables indexed by changes in one or more additional variables. Small multiples are described as multivariate, high-density, efficient, and narrative designs that facilitate comparison of complex data sets. See Figure 5.7 for an example. Small multiples are a technique for clustering data and are quite effective when paired with other graphical techniques (e.g. Dos Santos and Brodlie, 2004; Kocherlakota and Healey, 2009).
5.3 Chapter summary

This chapter presented some basic types of multivariate representations, including relational scatter plots, density plots, and glyphs. Novel variants of these basic types of representations tailored to the challenges of Design for Human Variability were also presented, including accommodation-encoded scatter and density plots, and the use of humanoid glyphs to represent human variability. The chapter also reviewed basic arrangements of representations, including interactivity, pairing, and small multiples.

The next chapter combines these graphical components in various ways and tests their resulting effectiveness for communicating human variability and accommodation. The next chapter explores two key research questions via analysis of two experimental studies. The questions are: (1) which methods of visualization lend themselves well to the challenges of DfHV, and (2) how may different visualizations be effectively integrated to produce visual design tools with output useful for decision-making and evidence generation?
Chapter V introduced several techniques for allowing designers to visualize and tradeoff body size data with dimensions of a product or environment. As a review, these include: encoded scatter plots, density/contour graphs, and representations using humanoid glyphs, and ways of presenting these representations, including interactivity, pairing, and small multiples. The purpose of this chapter is to describe the results of two experimental studies in which these techniques were evaluated by students and professionals acting as “designers”. This chapter often refers to the participants of the studies as designers.

The purpose of the first study was twofold: (1) evaluate the use of interactivity as a means for applying anthropometric data, and (2) compare this new interactive approach with a traditional approach, tables of percentiles of anthropometry. The interactive implementation consists of a web interface that permits interactivity with scatter plots by way of sliders and real-time feedback. Performance of this tool is compared with participants’ performance using static tables showing percentiles of anthropometry. Such static tables are a very common, traditional tool for designing for body size. Participants were asked to solve two design problems using the two tools and then provide feedback on their experiences. Therefore, results from the first experiment include both objective and subjective participant responses.

The second study was primarily concerned with the types of representations that designers were best able to understand and the types of representations they most preferred. Comprehension was assessed by presenting participants with several
representations and then asking a question about each one. Preference was assessed by asking the participant to rank four plots that show similar information in different ways. The second study also included a detailed section on demography and background, along with various questions about the design process employed by the participant for solving problems involving anthropometry. The demographics and design process data were covered in Chapter IV.

The results of the two studies are presented across the next two sections, along with a subsection discussing the key findings for each study. The third section summarizes conclusions from the two studies that may be used to inform the development of new tools for designing for body size.

6.1 Study 1: Interactivity

The first study was a within-subjects, web-based study. Over a period of seven months, fifty-one participants with varying experience using anthropometry for design solved two problems using two types of tools: (1) a traditional tool consisting of tables of percentile values for relevant anthropometry (i.e., 1st, 2nd, 5th, 10th, 25th, 50th, 75th, 90th, 95th, 98th, and 99th percentile values for each measure), and (2) the dynamic, web-based interface depicted in Figure 6.1. ANSUR data were used to create both representations.

The web-based interface allows a user to pick anthropometric dimensions of interest from a list box, select desired ranges of data using sliders, and plot the data with color coding that indicates accommodation (accommodated points are blue and disaccommodated points are red). Percent accommodation on all measures is also indicated. A “symmetry” check box enables the option of ensuring symmetry of the selected range about the mean value for the dimension. The web tool permits simple and accurate solution of multivariate accommodation problems—the sliders set limits on an underlying population of anthropometry (ANSUR), and accommodation is calculated in a way similar to the virtual fit method.
6.1.1 Study 1 Methods

Participants used each tool to solve each of two problems to facilitate direct comparison of the results, but with different numeric goals to avoid users simply copying answers. Problem order did not vary among participants. The first problem served as a practice problem to acquaint the user with the tools—it asked participants to calculate the range in seated popliteal (knee) height and hip breadth necessary for 95% accommodation of the male population or 90% or 95% of the female population, depending on the tool. The second problem asked participants to calculate the range of shoulder widths and hip heights needed for 95% accommodation of the male population or 90% or 95% of the female population. Both problems and the requested design parameters for each are shown in Figures 6.2a and 6.2b.

The participants were evenly split into two groups—one group received the tables first and the other group received the web tool first—to avoid bias effects. Participants
(a) The first design problem. Associated anthropometry is seated popliteal (knee) height and hip breadth.

(b) The second design problem. Associated anthropometry is hip height and biacromion breadth.

Figure 6.2: Problem specification for the first and second tasks.

were drawn from two Penn State Industrial Engineering Courses (PSU-327 and PSU-547) for which the study was offered for extra credit, and a small number of practicing engineers from the Army Research Lab’s Human Research and Engineering Directorate MANPRINT Methods and Analysis Branch (ARL). The study was approved by appropriately constituted internal review boards at both institutions. Note that the interface changed slightly as the study progressed—participants in the PSU-547 group received the interface shown whereas participants in the PSU-327 and ARL groups received an interface without the “symmetry” feature. The PSU-327 (2) group received a streamlined questionnaire.
6.1.2 Study 1 performance metrics

Several measures were collected from participants, including background and demographic characteristics, their responses to the problems, the time required for completion of the problems, and a subjective assessment of the tools. Simpson et al. (2007) investigate response delay and training on user interfaces in engineering design and propose an evaluation scheme wherein effectiveness and efficiency are key metrics. These metrics are used in the present work, and subjective satisfaction is added as a third area of evaluation.

Effectiveness is expressed by determining the accuracy and accommodation percentage yielded by participants’ responses. Accuracy is calculated by comparing participant answers (a and b) with a true answer predetermined by the experimenters (α and β), as in Equation 6.1. The equation normalizes the closeness of each participant’s solution to a predetermined solution for comparison.

\[
\text{accuracy} = 1 - \frac{1}{4} \left( \frac{|a_{\min} - a_{\min}|}{a_{\min}} + \frac{|a_{\max} - a_{\max}|}{a_{\max}} + \frac{|b_{\min} - b_{\min}|}{b_{\min}} + \frac{|b_{\max} - b_{\max}|}{b_{\max}} \right) \times 100\% \quad (6.1)
\]

Accommodation is calculated by imposing the limits given by participant responses (a and b) on the set of anthropometry under investigation. If a particular anthropometric data point lies outside the limits given by a and b, that point is said to experience disaccommodation. This is an application of the virtual fit methodology (Parkinson et al., 2007).

Efficiency is evaluated by comparing time required to solve a problem with accuracy. Efficiency is presented graphically by plotting the change in solution time against change in the accuracy between the web tool and tables.

Satisfaction is evaluated by asking participants to judge their experiences with each tool. First, participants are asked to rate their confidence that they have correctly identified a correct result on a 10-point scale. Second, participants are asked to respond to the four questions featured in Figure 6.7 on a 5-point Likert scale.
Figure 6.3: Deviation of participant responses from the predetermined answer for the tables and web tool for the second problem (the first problem is considered a practice problem). Accommodation achieved by each response is indicated below the responses—accommodation is calculated for saddle height and handlebar width combined.

### 6.1.3 Study 1 Results

Figure 6.3 shows participant responses across the various groups for the web tool and tables for the second problem. Table 6.1 summarizes results given by the objective performance metrics. Figure 6.4 evaluates efficiency for both problems. It compares accuracy and solution time for the web tool versus the accuracy and solution time for the tables. As such, positive values on the ordinate or abscissa indicate that results from the web tool took longer to obtain or were more accurate than results for the tables.

**Table 6.1: Summary of the results for the objective performance assessment for study 1.**

<table>
<thead>
<tr>
<th>Problem</th>
<th>Metric</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1-Tables</td>
<td>Accuracy</td>
<td>91%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>204 sec</td>
<td>143 sec</td>
</tr>
<tr>
<td>P1-Web</td>
<td>Accuracy</td>
<td>92%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>302 sec</td>
<td>237 sec</td>
</tr>
<tr>
<td>P2-Tables</td>
<td>Accuracy</td>
<td>96%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>Accommodation</td>
<td>73%</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>131 sec</td>
<td>91 sec</td>
</tr>
<tr>
<td>P2-Web</td>
<td>Accuracy</td>
<td>97%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>Accommodation</td>
<td>77%</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>177 sec</td>
<td>143 sec</td>
</tr>
</tbody>
</table>
respectively. Figure 6.5 shows a similar representation for the second problem compared with the first problem. Similar to Figure 6.4, positive values on the ordinate or abscissa indicate that results from the second problem took longer to obtain or were more accurate than results for the first problem, respectively.

Figures 6.3 and 6.4 show that designers are slightly better able to specify enough adjustability when using the web tool. The web tool slightly increased participants’ accuracy and estimates of accommodation, but required more time to solve the problem. Figure 6.4a shows an average increase in accuracy of about 1% and average increase in solution time of about 98 sec for the web tool compared with the tables for the first problem; for the second problem, Figure 6.4b shows an average increase in accuracy of about 1% and average increase in solution time of about 46 sec for the second problem. Figure 6.5 indicates that practice improves user performance—26 participants were faster and more accurate using the tables for problem 2, and 37 participants were faster and more accurate with the web tool. Of all the quantities listed in Table 6.1, a two sample t-test indicated statistical significance only between the following quantities:

- Accuracy for P2-Web vs. P1-Web ($p < 0.05$)
Figure 6.5: Change in accuracy and time between the first and second problem for tables and the web tool. Points on the right half indicate better accuracy for problem 2, and points on the upper half indicate faster performance for problem 1. The red cross locates the mean.

- Time required for P1-Web vs. P1-Tables ($p < 0.05$)
- Time required for P2-Web vs. P1-Web ($p < 0.005$)
- Time required for P2-Tables vs. P1-Tables ($p < 0.05$)

Figure 6.6 compares self-rated participant confidence on a 1-10 scale for the two tools. Figure 6.7 shows the distribution of responses for four of the five follow-up questions asked in the subjective portion of the assessment. The fifth was omitted due to an error in wording—some participants received the question “the solution obtained using the tool did not seem reliable or complete” while others received the question “the solution obtained using the tool seemed reliable and complete”. The Wilcoxon Sign Test was applied to the confidence scores and the four subjective questions assessing decision-making power of the tools. The results of the test show that the differences in confidence were statistically significant (at $p < 0.005$). Likewise, differences for the four follow-up questions were also statistically significant (at $p_1 < 0.001$, $p_2 < 0.001$, $p_3 < 0.005$, $p_4 < 0.001$, respectively).
6.1.4 Study 1 Discussion

The objective performance assessments for the study are not conclusive—that is, the study was unable to show that designers objectively perform better using either tables or the interactive web tool. However, a few observations may be made. The results from the tables seem to specify too little adjustability, indicated by Figure 6.3 (particularly for seat height). As mentioned in a previous chapter, underaccommodation (i.e., too little adjustability) is to be expected when a univariate method, such as a table of anthropometry, is applied to a multivariate problem.

Designers were more familiar with the tables before beginning the study. The background assessment revealed that 67% of participants claimed familiarity or expertise using tables of anthropometry, compared with 47% that claimed familiarity or expertise using population models (the web tool features a population model with raw anthropometric data). This familiarity with tables likely translated into a better understanding of how to use the tables to achieve the design goal. Indeed, the study found a statistically significant increase in accuracy when using the web tool to solve the second problem (97% accuracy) when compared against the first problem (92% accuracy). A modified study procedure wherein participants have more time to explore the web tool—or perhaps receive a brief tutorial in its use—would likely improve designer performance.
The results of the tool would influence non-expert decision-makers.

The tool helped me understand the problem and which users will be accommodated or disaccommodated by the design.

The tool was difficult to implement.

The tool provides compelling evidence for decision-making.

Figure 6.7: Subjective post-response assessment of decision-making power for both tools.

The subjective performance assessments were more conclusive and consistent. For every question asked, differences in subjective responses about the web tool and tables were statistically significant. The study found that designers were more confident that their answers using the web tool provided an accurate solution (7.1/10) as compared with the tables (mean 5.6/10). Interestingly, while reported confidence was significantly higher for the web tool, 43% of participants reported a confidence in the results of the tables between 7 and 10, which would suggest a passable solution by convention. This indicates
that they may not be aware of the limitations of using univariate tables to solve problems involving multiple measures of anthropometry.

The study also found that, when compared with tables, participants judged the web tool: (1) better able to influence decision-makers, (2) better able to help in understanding the problem and which users are accommodated, (3) easier to implement, and (4) better in providing compelling evidence for decision-making. These are important results. In addition to achieving more accurate solutions to multivariate problems, a key objective of improved tools for working with anthropometry is to better communicate design performance and tradeoffs to the designer and other decision makers. Overall, participants in this study performed at least as well using the interactive tool as compared with tables and were receptive to such a representation for working with anthropometry.

6.2 Study 2: Representations

Like the first study, the second study is also web-based. A fundamental question from that survey addressed in this section is: if tables are not the best representations for displaying anthropometry, what would be better? How should improved tools look? To help answer this question, 83 participants completed the survey over a period of seven weeks, which assessed their background and demographics, design process, characteristics of humanoid glyphs, comprehension of several types of figures displaying anthropometry and product design dimensions, and preference for any of these types of figures. This section focuses on the last three of these five parts—glyphs, comprehension, and preference for various representations. Responses addressing preferred design processes were discussed in Chapter IV.

6.2.1 Study 2 Overview

Demographics and background for study participants were introduced in Chapter IV. As review, 94 participants responded to the invitation to take part in the study and completed some of the survey, and 83 participants finished the survey. Potential participants were identified based on their involvement in human factors/ergonomics (HF/E) at the student or professional level. The study was offered for extra credit to 48 students in
IE-327 (Introduction to Work Design) at Penn State and was circulated to 85 employees at the Army Research Lab’s Human Research and Engineering Directorate. The study was also advertised to the mailing list of the Penn State Chapter of the Human Factors and Ergonomics Society and an ergonomics-related LinkedIn discussion group\(^1\). The study received approval from an appropriately constituted internal review board at The Pennsylvania State University.

The organization of the study follows:

- **Part 1: Demographics and background.** The study began with demographic questions, including: age, any cognitive or physical impairments that might affect the survey, geographic region, highest level of school/highest degree received, and occupation. The study also asked several relevant background questions, including where any training in human factors/ergonomics took place, familiarity with purchasing or designing products for users, and familiarity with several topics related to human size (e.g., anthropometry, boundary manikins, etc.).

- **Part 2: Design process.** The second part of the survey asked a series of questions about the participant’s design process when considering human body size and shape, which are addressed in Chapter IV.

- **Part 3: Glyphs.** Part 3 of the survey asked participants to identify the BMI of two types of humanoid glyphs drawn at random from five possibilities each to determine if a high degree of detail is needed for qualitative comparison.

- **Part 4: Comprehension.** Part 4 of the survey asked one question each about a series of nine representations of human variability for design.

- **Part 5: Preference ranking.** Part 5 asked participants to rank their preference for three sets of four representations.

Chapter IV covers Parts 1 and 2. The following sections present the methods and results for Parts 3 through 5.

\(^1\)LinkedIn group: Dassault Systèmes Virtual Ergonomics, http://www.linkedin.com/groups?gid=1792209
6.2.2 Study 2, Part 3: Glyph detail

Two forms of the human-glyph are investigated that include different amounts of detail. A key question of this part of the survey is, are there advantages to considering great detail when constructing the human-glyphs, or do simple line drawings scaled by one or more factors suffice?

Participants were presented with one of each of the types of glyphs shown in Figure 6.8 (BMI was not labeled). Participants were first shown one scaled drawing selected at random from the five possibilities followed by one CATIA Human rendering selected at random from the five possibilities. They were asked whether they judged each figure to be: (1) underweight (BMI less than 19), (2) normal weight (BMI between 19 and 25), (3) overweight (BMI between 26 and 30), or (4) obese (BMI greater than 30). The
height (stature) for each of the figures in Figure 6.8 was held constant. Figure 6.8a was encoded by proportionally scaling the human figure outline shown in the horizontal direction. Figure 6.8b was created in CATIA Human Builder (Dassault Systemes, 2012) by holding the stature constant at 1860 mm and varying only the weight as shown in the figure. According to the Dassault-Systèmes website, CATIA Human depicts roughly 100 anthropometric measures, and many of them adjust according to changes in weight.

The human-glyphs were modified only by weight to avoid confounding effects. It is assumed to be much easier for the viewer to compare one parameter at a time (e.g., weight) as opposed to multiple parameters at a time (e.g., weight and stature). This strategy is maintained throughout the other sections of the survey. For instance, although the glyphs shown in Questions 3 and 5 in Table 6.3 encode both stature and weight, the accompanying question asks only about the relationship of fit with BMI or stature. Practical use of glyphs would likely encode multiple dimensions onto one glyph, but viewers may still mentally separate variations on each dimension independently while not compromising the utility of the human-glyph as an analysis tool.

The results comparing a simple scaled glyph with a more intricate DHM manikin are presented in Table 6.2. From the table, it may be observed that the majority of participants correctly interpreted both glyphs. More participants judged the scaled drawing accurately compared with the CAD manikin, however the differences were not statistically significant. A Wilcoxon Signed-Rank test failed to reject the null hypothesis that participants achieve an equal success rate in judging the scaled drawing and CAD manikin, with $Z = -1.86$, $p = 0.063$.

Table 6.2: Summary of the results for the first part of Study 2, showing the number of participants who correctly assessed the figure, underestimated BMI, and overestimated BMI.

<table>
<thead>
<tr>
<th></th>
<th>Scaled Drawing</th>
<th>DHM Manikin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>62 (65%)</td>
<td>49 (52%)</td>
</tr>
<tr>
<td>Underestimated BMI</td>
<td>26 (27%)</td>
<td>30 (32%)</td>
</tr>
<tr>
<td>Overestimated BMI</td>
<td>7 (7%)</td>
<td>16 (17%)</td>
</tr>
</tbody>
</table>
Note that the human-glyphs used throughout the remainder of the study are exclusively of the scaled-drawing type. It is later demonstrated in the results that the efficacy of the drawing-type and DHM-type human-glyphs are approximately equal (for estimating weight), and so only the drawing-type is used for consistency in the results.

6.2.3 Study 2, Part 4: Comprehension

In Part 4 of the study, participants were presented with nine different types of figures and were asked to answer a corresponding multiple choice question about each figure. This evaluation served two functions: (1) assess the interpretability of each of the types of figures, and (2) familiarize the participant with the various types of representations in preparation for them to rank them in order of preference in Part 5. Each figure and the corresponding questions and answers are listed in Table 6.3. There is one correct answer for each representation, shown in bold in the table. Table 6.4 summarizes the percent of participants with correct responses, incorrect responses, “not enough information” responses, and “I don’t know” responses. Comments on the performance for each of the types of representations follow next.

Table 6.3: Questions and representations are shown for each of the nine assessed in the comprehension section of the survey (Part 4). The correct answer to each question is shown in bold.

<table>
<thead>
<tr>
<th>Representation</th>
<th>Question &amp; Answer</th>
</tr>
</thead>
</table>
| 1. Select the response that best characterizes the representation shown. Only one response is correct. | 1. A. Taller people are more likely to fit the product.  
B. People with lower BMI are more likely to fit the product.  
C. People with higher BMI are more likely to fit the product.  
D. There is not enough information shown to relate fit to stature or BMI.  
E. I don’t know. |

Continued on next page
Table 6.3: Questions and representations are shown for each of the nine assessed in the comprehension section of the survey (Part 4). The correct answer to each question is shown in bold.

<table>
<thead>
<tr>
<th>Representation</th>
<th>Question &amp; Answer</th>
</tr>
</thead>
</table>
| ![Representation 1](image1.png) | 2. Select the response that best characterizes the representation shown. Only one response is correct.  
   - A. Group B females are more likely than group A females to fit the product.  
   - B. Group A males are more likely than group B males to fit the product.  
   - C. Group A females are more likely than group B females to fit the product.  
   - D. There is not enough information shown to relate fit to group or product.  
   - E. I don’t know. |
| ![Representation 2](image2.png) | 3. Select the response that best characterizes the representation shown. Only one response is correct.  
   - A. People with lower BMI are most likely to fit the product.  
   - B. People with higher BMI are more likely to fit the product.  
   - C. Taller people are more likely to fit the product.  
   - D. There is not enough information shows to relate fit to stature or BMI.  
   - E. I don’t know. |

*Continued on next page*
Table 6.3: Questions and representations are shown for each of the nine assessed in the comprehension section of the survey (Part 4). The correct answer to each question is shown in bold.

<table>
<thead>
<tr>
<th>Representation</th>
<th>Question &amp; Answer</th>
</tr>
</thead>
</table>
| ![Image of a graph showing frequency distribution](image1) | 4. Select the response that best characterizes the representation shown. Only one response is correct.  
- A. Men are more likely than women to fit the product.  
- B. Women are more likely than men to fit the product.  
- C. Men and women are equally likely to fit the product.  
- D. There is not enough information shown to relate fit to gender.  
- E. I don’t know. |
| ![Image of a graph showing product specification X](image2) | 5. Select the response that best characterizes the representation shown. Only one response is correct.  
- A. People with tall stature are most likely to fit the product.  
- B. People with short stature are more likely to fit the product.  
- C. People with low BMI are most likely to fit the product.  
- D. There is not enough information shown to relate fit to stature.  
- E. I don’t know. |
| ![Image of a table showing BMI and product specifications](image3) | 6. Select the response that best characterizes the representation shown. Only one response is correct.  
- A. People that fit tend to be taller than people that do not fit.  
- B. People that fit tend to have lower BMI than people that do not fit.  
- C. People that fit tend to choose greater values for product specification x and y than people that do not fit.  
- D. There is not enough information shown to relate fit to body dimensions or product specifications x and y.  
- E. I don’t know. |

Continued on next page
Table 6.3: Questions and representations are shown for each of the nine assessed in the comprehension section of the survey (Part 4). The correct answer to each question is shown in bold.

<table>
<thead>
<tr>
<th>Representation</th>
<th>Question &amp; Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td>7. Select the response that describes a change to the adjustment range box in the figure that will result in the greatest improvement in the portion of the target population that will fit the product.</td>
</tr>
<tr>
<td><img src="image2.png" alt="Diagram" /></td>
<td>- A. Increasing both product specification limits by 5 units in each direction.</td>
</tr>
<tr>
<td><img src="image3.png" alt="Diagram" /></td>
<td>- B. Decreasing lower product specification X by 20 units.</td>
</tr>
<tr>
<td><img src="image4.png" alt="Diagram" /></td>
<td>- C. Increasing upper product specification Y by 20 units.</td>
</tr>
<tr>
<td><img src="image5.png" alt="Diagram" /></td>
<td>- D. There is not enough information shown to recommend changes to adjustability that increase the number of people that fit.</td>
</tr>
<tr>
<td><img src="image6.png" alt="Diagram" /></td>
<td>- E. I don’t know.</td>
</tr>
</tbody>
</table>

8. Select the response that best characterizes the link between body size (stature and BMI) and preferred response (x and y).  
- A. People with taller stature tend to select greater values of product specification x.  
- B. People with greater BMI tend to select lower values of product specification x.  
- C. Users’ preference for product specifications x and y are dependent on their stature, but not BMI.  
- D. There is not enough information shown to relate stature and BMI to preferred product specifications x or y.  
- E. I don’t know.  

9. Select the response that gives the product specifications X and Y that achieve fit for the greatest portion of the population shown.  
- A. Product specification X has range 710 to 900 and product specification Y has range 30 to 100.  
- B. Product specification X has range 710 to 900 and product specification Y has range 100 to 170.  
- C. Product specification X has range 900 to 1090 and product specification Y has range 30 to 100.  
- D. There is not enough information shown to specify product specifications X and Y that achieve fit for the greatest portion of the target population.  
- E. I don’t know.
Plain scatter

The representation in Question 1 is a plain scatter plot—that is, dots are used to plot combinations of stature and BMI. Accommodation is then encoded for each point by coloring the points red or blue. The representation in Question 2 pairs a plain scatter plot with a histogram. In Question 9, plain scatter plots are tiled in a small multiple configuration. These plots were judged correctly by 69%, 52%, and 66%, respectively, of participants. Question 1, additionally, scores amongst the top three ratings in terms of greatest number of correct responses, least number of incorrect responses, and fewest “I don’t know” responses. This would indicate that participants were most familiar with this sort of plot and had relatively little difficulty understanding it.

Tables

A table summarizing the interaction of a population of users with a prototype appears in Question 6. 69% of participants were able to correctly interpret this representation, with an incorrect response rate of only 9%, among the lowest three. Like the plain scatter plot, familiarity likely aided participants’ ability to understand this representation.

Glyphs

The representation in Question 5 makes use of glyphs in an ordered chart—that is, humanoid glyphs similar to Figure 6.8a are stacked next to each other according to BMI and then stature. Glyphs are also used in Question 3 in a relational scatter plot and in Question 4 in another relational scatter plot paired with a histogram. These plots were judged correctly by 63%, 59%, and 24% of participants, respectively. A relatively small percentage of participants answered “I don’t know” for these questions (7%, 5%, and 6%, respectively). Of the three usages, the highest scores were achieved for glyphs appearing in an ordered chart, followed by the standalone scatter plot.

Density plots

A density plot appears in Question 7 and 8, in both cases indicating where the concentration of preferred responses is highest. 50% of respondents correctly interpreted
the figure in Question 7, a middling score for the entire study population. This plot received the greatest percentage of incorrect responses (35%). The question associated with this figure is subtly different from many of the others—it asks participants to identify how the product dimensions shown in the figure may be improved to accommodate more people. A correct interpretation would recognize that centering the adjustment range over the highest concentration of users will lead to greater performance. Non-students (HF/E professionals) were better able to interpret this figure, yielding a correct response rate of 65% (among the highest three for that group). Participants performed better in Question 8 (63% accuracy with only 1% responding “not enough information”).

Pairing

One technique for displaying multivariate data described in Chapter V is displaying multiple views of two-variable plots, a technique referred to here as “pairing”. Pairing was used in Question 2 and 4, and in both cases, scores revealed that participants struggled to integrate key information from the two representations to identify the correct response. In addition to a relatively low rate of correct responses (52% and 24%, respectively), in both cases, a relatively large percentage of participants responded with “not enough information” (17% and 43%, respectively). These representations performed even worse among the non-student group.

Small multiples

Small multiples are used as a technique for encoding additional information onto density and scatter plots in Questions 8 and 9, respectively. Participants responded with slightly greater accuracy for the small multiples with scatter plots (66%), as compared to the small multiples with density plots (63%). Both of these representations achieved among the lowest three scores for the “not enough information” response.
Table 6.4: Summary of participants’ comprehension of the various representations. The data show the percentage of participants responding with the correct answer (✓), an incorrect answer (✗), “not enough information” (Ø), and “don’t know” (?), respectively. An asterisk appears next to the top three scores in each column.

<table>
<thead>
<tr>
<th>Representation(s)</th>
<th>All participants</th>
<th>Non-students</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>1</td>
<td>69%*</td>
<td>12%*</td>
</tr>
<tr>
<td>2</td>
<td>52%</td>
<td>19%</td>
</tr>
<tr>
<td>3</td>
<td>59%</td>
<td>12%*</td>
</tr>
<tr>
<td>4</td>
<td>24%</td>
<td>26%</td>
</tr>
<tr>
<td>5</td>
<td>63%</td>
<td>17%</td>
</tr>
<tr>
<td>6</td>
<td>69%*</td>
<td>9%*</td>
</tr>
<tr>
<td>7</td>
<td>50%</td>
<td>35%</td>
</tr>
<tr>
<td>8</td>
<td>63%</td>
<td>21%</td>
</tr>
<tr>
<td>9</td>
<td>66%*</td>
<td>15%</td>
</tr>
</tbody>
</table>
6.2.4 Study 2, Part 5: Preference

In Part 5 of the study, participants were presented with three questions each showing four representations. The sets are various combinations of the representations introduced in the previous section, including tables, glyphs, density contours, and small multiples. The three questions asked users to rank available plots from 1 (most preferred) to 4 (least preferred). The three questions asked users, respectively, to compare available representations in their ability to:

1. Demonstrate the link between body size and preferred product specifications
2. Demonstrate that fit is affected more by stature than BMI in the figures shown
3. Demonstrate that more people with high BMI will fit if adjustability for product specification Y is increased in the figures shown

The three sets of representations are shown in the pairwise comparison charts of Tables 6.5, 6.6, and 6.7. While the study asked participants to rank the four representations, it is useful to construct pairwise comparisons to better understand preference for the figures.

Table 6.5 shows that participants ranked representations B, C, and D approximately equally. This result is not surprising since all three of those representations are small multiple displays. These small multiples were preferred over a scatter plot with glyphs. Since preference rankings for figures B, C, and D resulted in a three-way tie, it is helpful to consult the 1st-place ranking data, also shown in Table 6.5. Representation D was most often ranked first among the figures, and so may be considered the most preferred of this set, followed by representation B and C, and then representation A. Representation D used plain scatter plots in a small multiple configuration—two representations performing well in the comprehension assessment of Part 4.

Table 6.6 shows that participants ranked representation C (plain scatter) first, A (ordered glyph chart) second, D (table) third, and B (scatter glyph) fourth. This is consistent with both the comprehension assessment data and the preference ranking of the set of representations shown in Table 6.5.
Table 6.7 shows that participants ranked representation C (paired plain scatter) first, B (scatter glyph) second, A (density small multiple) third, and D (density small multiple) fourth. As for Table 6.5, preferences for the two small multiple displays were very similar. It is noteworthy that the objective for this preference ranking differed slightly from the others; users were asked to select the plot that indicates how design dimensions may be improved to accommodate more people. Small multiples do not appear to be preferred for this task, but as before, plain scatter plots were favored by respondents.
Table 6.5: Pairwise comparison chart for the first set of preference-ranked representations—participants were asked to rank their preferred representations according to their ability to demonstrate the link between body size and product specifications. Percent of respondents that rank the representation in the column over the representation in the row is shown for each cell—the number of times that a majority of participants ranked the representation in the column higher is totaled next to “Number of wins”. The “1st place rank” row indicates the percentage of respondents ranking the indicated representation 1st of 4.

<table>
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<td>27%</td>
<td>19%</td>
<td>22%</td>
<td>33%</td>
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</table>
Table 6.6: Pairwise comparison chart for the second set of preference-ranked representations—participants were asked to rank their preferred representations according to their ability to demonstrate that fit is affected more by stature than BMI.
Table 6.7: Pairwise comparison chart for the third set of preference-ranked representations—participants were asked to rank their preferred representations according to their ability to demonstrate that more people with high BMI will fit if adjustability for product specification Y is increased.

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<td>28%</td>
<td>39%</td>
<td>18%</td>
</tr>
</tbody>
</table>
6.2.5 Study 2 Discussion

This discussion parallels the organization of the results—glyph detail, figure comprehension, and figure preference are discussed in this order. Key observations and conclusions from the second study are then discussed last. Anecdotal feedback at the end of the survey was also solicited from participants—13 of the participants provided additional comments. Some of these comments are included with the discussion, where appropriate.

Humanoid glyphs

A key conclusion of Part 3 of the second study is that encoding intricate detail in expressing weight (BMI) in human-glyphs was not found to enhance viewers’ ability to interpret the weight of the human-glyph. In fact, in the study, results were better for a simple drawing scaled proportionally in one direction as compared with a complicated digital manikin reconfigured on many dimensions (although not at a statistically significant level). This is not surprising; the scaled drawing exaggerates the variability with the intent of making it plainly obvious.

The implications of this conclusion are important. The time, complexity, and investment in software resources required to generate intricate digital human manikins might inhibit their use as human-glyphs. If a designer can generate a simple proportionally scaled human-glyph with similarly effective results to communicate a particular parameter, the impetus to utilize human-glyphs would be greater.

How might glyphs benefit analysis of a problem? In Question 3 of Table 6.3, the accumulation of wide glyphs in the upper right corner indicate that heavier users tend to select product specifications in that range. By pairing this visualization with an encoding of accommodation (red/blue coloring), the designer has knowledge that many users in that region are disaccommodated. The ordered chart in Question 5 of Table 6.3 permit viewers to slice data using different rules (e.g., order) to discover trends while preserving an appreciation for the multivariate variability. Within an interactive design tool, both of these visualizations would permit intuitive exploration of data.

However, the particular strategy for generating the scaled drawings should be carefully considered. In this work, the human figure was traced from a sketch appearing
in an interim report for the ANSUR data, similar to Figure 6.9. The figure was then scaled proportionally with variation in BMI. Such a figure is not necessarily representative of the build of individuals in a target population, and contains a great deal of extraneous data. As one respondent noted, “I think a more abstract representation of BMI would be more efficient and easier to interpret than the squished human figures [...] The problem with squishing the figures is that head and other body segments are distorted unrealistically, plus the figure contains a lot of unnecessary information (e.g., arm lengths).”

Training or tutorials on the proper use of glyphs might also enhance their comprehension and designers’ preference for them. Another respondent remarked, “The scaled human figures arranged in rows were the most unclear representation and [I am] not sure how it characterizes fit. For example, does row order or position in row indicate likelihood of fit?” The participant had not picked up on the clue that red figures represented disaccommodated whereas blue figures represented accommodation. Figures were ordered by either BMI or stature to permit observation of accommodation trends across these variables. Such nuance allows an expert to quickly scan the data for trends, but such detail can be difficult for a novice to notice and process.

Using humanoid glyphs to represent user variability in graphs or charts is a novel concept and should be explored further. As one participant reflected, “the ones with people inside are much more clear than [the] others.” Allowing designers to visualize the
size of individual data points may permit greater insight and intuition, which are useful characteristics of visual evidence for decision makers.

**Figure comprehension and preference**

Among the various types of graphs, scatter plots (and arrangements of scatter plots) were best understood by participants. Tables were also well understood. Similarly, glyphs were well understood, but scores were higher for glyphs appearing in an ordered chart (i.e., as in Question 5) as opposed to a relational graph (i.e., Question 3). Results show that comprehension was poorer for the density plots. Scores for non-students generally did not differ significantly from all participants, except for the single density plot in the design task, where non-students performed significantly better.

Participants most favored the use of accommodation-encoded scatter plots, but scatter graphs with encoded glyphs were not always preferred. The paired plain scatter plots were the most preferred for the design task described in Table 6.7.

Among the various arrangements of graphs, small multiples were relatively well understood. However, pairing two unrelated graphs was not as effective for communicating the data (e.g., Question 2 and 4). Glyphs employed in paired graphs—two techniques not generally favored by respondents—yielded the worst performance in terms of comprehension (Question 4).

In general, any combination of multiple displays requiring mental integration of information is cognitively challenging. As mentioned in Section 5.2, the proximity compatibility principle (Wickens and Carswell, 1995) suggests that good display design requires close proximity between multiple displays (e.g., nearness in space, common colors or patterns, etc.). The proximity compatibility principle lends insight to the experimental results of this study. As would be expected, comprehension of the small multiples is fairly high, since they capitalize on several strategies for mental proximity including close spatial arrangement and repetition of shapes and patterns. On the other hand, the paired displays showing a dissimilar scatter plot and histogram violate several principles of mental proximity and therefore suffer worse comprehension scores.
General observations

One challenge in interpreting the results of the study is the novelty of the representations. As one respondent noted, “This was the first time I have seen some of the plots. I think I would like them more and be more proficient using them once I have had more experience reading them and creating them.” The comprehension section was intended to both assess the interpretability of the representations for novices and acquaint the participant to the various types of representations so that they were better equipped to express their preference in Part 5. However, other survey strategies might more distinctively separate the training and assessment duties. Certainly, comprehension scores—and preferences—would change as designers become more familiar with the various types of representations and their arrangement.

The implications of this survey are significant, however. Visualization of physical ergonomics problems involving multivariate anthropometry has long been problematic, and as a result, practitioners in the field have had limited access to tools for design and evaluation. Human-glyphs and small multiples, for instance, are building blocks by which powerful visualizations of human variability may be constructed that permit designers to make both broad and fine evaluations.

6.3 Conclusions from the studies

The goal of the first study was two-fold: demonstrate the advantages of new tools for designing for human variability and explore interactivity as such a tool. The primary goal of the second study was to determine the attributes of new decision-making tools for designing for human variability and the visual evidence they produce. To this end, there are several generalizable guidelines that may be asserted from the experimental results presented in this chapter.

1. Interactivity is a useful strategy for tools for designing for human variability. While the objective results (i.e., accuracy and time required) from the first study did not indicate statistically significant differences between traditional tables and an interactive tool, subjective measures indicated that designers were more confident, better able to influence
non-expert decision makers, and had a better understanding of accommodated and
disaccommodated users for the interactive tool as compared with traditional tables. All of
these findings are statistically significant.

2. **Representative humanoid glyphs are insightful and need not be intricate to be effective.** The
results of the second survey found that simpler representations involving glyphs—for
instance, an ordered chart—yielded better comprehension by designers as opposed with
glyph-encoded scatter plots. Glyphs need not be intricate figures constructed with digital
human modeling software to be effective in communicating qualitative relationships.
Simple scaled drawings suffice.

3. **Appeal to designers’ pre-existing visual knowledge when possible.** For instance, despite
the insight that glyph-encoded graphs may provide to expert designers, novices to this
type of representation may have trouble understanding it (novices capitalize on the salient
features of the figures without considering their intricacies). This is not to say that such a
representation should not be used, but the most familiar or easily understandable figure
should be used when possible. This study found that scatter plots were a familiar type of
representation that were well understood and favored by participants. Density plots were
not found to be as well understood or favored, despite their prevalence.

4. **Follow the proximity compatibility principle when constructing representations with
multiple views.** In this study, small multiples were found to effectively display multiple
views of information encoding several different variables. On the other hand, paired
but dissimilar figures (e.g., a scatter plot and histogram) were not well-understood by
participants and should be avoided.

5. **Consider the purpose for the plot.** For instance, small multiples were favored as
a strategy for arranging information describing a problem, but were not favored for
recommending design changes. In this case, glyphs in a graph were found to be more
effective at communicating several dimensions of variability for making design change
recommendations. However, glyphs in graphs were not favored for the purpose of
description.

In the next chapter, these results are combined with the findings of the education
survey of Chapter III and interviews with design professionals in Chapter IV to develop
a set of recommendations for understanding body size in education and a broad set of principles for designing for human variability in practice. A prototype of a new mobile application for designers and evaluators of products designed for their users is also presented and discussed in the next chapter.
CHAPTER VII

CONTRIBUTIONS, RECOMMENDATIONS, AND FUTURE WORK

Key contributions of this dissertation are discussed in the first section of this chapter, followed by key findings from each chapter that represent the recommendations of the dissertation. After a review of these recommendations, a prototype mobile application (or “app”) that implements several of the recommendations is presented. Finally, the chapter concludes with limitations and recommended future work.

7.1 Contributions

This dissertation explores several facets of solving design problems considering anthropometry. From background to education to practice, Chapters II, III, and IV review related literature, educational programs and textbooks, and practices in industry related to designing products and environments for users’ physical size. Such a multifaceted review could not be found in the literature. The most recent review of ergonomics education (particularly course syllabi) found in the literature dates from 1992, and no comprehensive interviews of ergonomics practitioners specializing in physical body size could be found. Most importantly, these studies show that courses, textbooks, and practitioners do not adequately consider anthropometry in design, particularly for multivariate problems.

Key contributions of the dissertation are found in Chapters V and VI. These sections present new representations of human variability and ways of solving design problems that are not currently found anywhere else in the literature or practice. The representations combine and enhance traditional multivariate representations to provide designers with insight to make better decisions about human variability and accommodation. The
experimental studies provide guidance for the improvement of these representations in future iterations and the creation of new representations that adhere to best practices.

Taken together, the findings of these chapters may be applied in education, industrial practice, and practical design tools to improve the state of the art in designing for the body size of people in the products and environments they use. Applications in these areas are discussed next.

**Education**

Chapter III demonstrated that anthropometry is mentioned in many courses on physical ergonomics (89%) but gets only a small fraction of class time (9%). A few courses cover design tools (e.g., digital human modeling and universal design) or applications (e.g., vehicle ergonomics), but most do not. Similarly, the chapter also demonstrated that commonly used texts do not provide adequate resources. However, educators interviewed in Ireland were eager to find practical resources that they could implement in engineering design classes. Considering freely available, ubiquitous tools such as Wikipedia and YouTube, it is important that new and improved resources provide low barriers of entry to students and educators. Expensive textbooks that quickly grow outdated are not the answer. The guidelines and recommendations in this dissertation could easily find their way into the hands of students via distribution channels that are free or low-cost and may be kept current—YouTube and the Apple iBookstore are two examples. To improve the state of the art, future work should make use of these channels.

**Practice and Design Tools**

Practical guidance for designers that is freely accessible and easy to understand also has the ability to change the state of the art. Awareness is key, and this was reinforced in the interviews presented in Chapter IV. Designers and companies want to make products that people want to use—it is a win-win proposition. However, they often lack the tools and knowledge to do so, and they lack awareness of the problems and pitfalls of many traditional tools (e.g., designing for the average user and using univariate templates for multivariate problems). Chapter IV mentioned the National Disability Authority in
Ireland as a partner for this work. A key goal of that organization is to help designers consider body size in their products and environments. The work of the NDA and other similar advocates for effective design may give exposure and opportunities for the application of the work of this dissertation.

For both students and designers alike, mobile apps are useful for communicating and working. Their portability and interactivity make them a powerful tool for solving all kinds of problems. Any future work applying the principles from this dissertation should consider development of mobile apps—a prototype is suggested in Section 7.3. Another possibility for a practical design tool is a guide sheet like the Seven Principles for Universal Design (Story, 1998) outlining best practices in Design for Human Variability. No matter the form of the tools, they can provide the just-in-time resources that students and designers need to solve problems.

7.2 Recommendations

To effect improvements in education, practice, and design tools, a set of core recommendations are useful. Chapters II, III, IV, V, and VI provide several principles and findings that should guide efforts to design for the variability in body size for target user populations. This section reviews recommendations found in these sections.

Chapter II: DfHV best practices

Four best practices are listed in Chapter II that have emerged from the author’s previous works that should be included in approaches to designing for human variability or construction of quantitative tools for design. These best practices are summarized next. While they may not be applicable for every problem involving body size, they should be implemented when possible. Key references are listed next to several of the best practices, including some of the author’s previous work.

1. Carefully consider the target population. Designers should be cautious to select anthropometry that represents users for which they are designing. Secular and demographic trends should be considered to ensure products fit current and future
populations. See de Vries et al. (2010). If detailed anthropometry are unavailable for the intended user population, anthropometry may be synthesized from detailed data (e.g., ANSUR) and basic representative data (e.g., NHANES). See Parkinson and Reed (2009).

2. *Model actual user behavior.* Actual user behavior, rather than designer assumptions or off-the-shelf simulations, should be considered when possible. A preference study wherein an outcome measure is modeled as a function of anthropometry is one way to capture actual behavior. See Garneau and Parkinson (2009).

3. *Perform virtual fitting.* A virtual population is a collection of many anthropometric data points that characterize a target user population. Virtual fitting trials make use of these data to assess the fit of the virtual population on one or more product parameters, which then permits straightforward determination of accommodation. See Garneau and Parkinson (2011).

4. *Simultaneously consider multiple dimensions.* Virtual fitting allows for the simultaneous consideration of multiple variables because such a model considers only the outcome of anthropometric variability instead of relying on the kinematics of the user. This avoids the pitfalls of misapplication of univariate anthropometry and reliance on a “percentile man”.

**Chapter III: Physical ergonomics education**

The syllabi survey in Chapter III found that designing for variation in anthropometry in target populations does not receive detailed treatment in many physical ergonomics courses. Moreover, course resources (e.g., textbooks) for designing for anthropometry provide outdated, inappropriate, or insufficient data. Providing students with easily accessible, accurate, and appropriate data on body size is imperative. Similarly, providing students with practical guidelines for design would also be beneficial.
Chapter IV: Designer insights

A few areas of concern emerged from the one-on-one interviews and web survey with design practitioners. These yield several practical guidelines for informing new tools and resources for designing for body size, which are summarized next.

1. *Properly consider design goals.* Industry standard “5th to 95th” percentile accommodation goals may be adequate, provided that designers properly understand what this goal means (i.e., capture 90% of the overall variability in the population). Continued education about the danger of designing for the mean is warranted, considering that 11% of respondents to the web survey indicated that they would aim to design for average users.

2. *Advertise available anthropometric data and communicate its appropriateness.* Many design practitioners identified the lack of representative and reliable anthropometric data as a major challenge. Many designers—particularly general design practitioners and not ergonomics specialists—were unaware of various sources of data available online and their appropriateness for a particular population. Efforts to advertise available data and ensure designers understand its appropriateness for various applications are advisable.

3. *Develop practical design tools.* Digital human modeling (DHM) is a common tool used among specialists. However, the high cost of DHM software prevents its use in many organizations that would otherwise benefit from it. Moreover, properly applying DHM tools requires substantial user training or experience. Basic tools should be developed and made accessible to designers for properly understanding and applying anthropometry. Any tools should be useful for practical design and evaluation.

4. *Enhance awareness of tools and guidelines.* Many designers would simply benefit from knowledge about the existence of already available tools and resources. A primer or guide to available resources would help many designers.
Chapter V and VI: Effective representations of human variability

Several generalizable guidelines for creating multivariate representations of human variability were proposed and evaluated in Chapters V and VI. These guidelines are summarized next.

1. **Interactivity is a useful strategy for tools for designing for human variability.** An interactive tool was judged by participants to yield more confidence, better ability to influence non-expert decision makers, and better understanding of accommodated and disaccommodated users as compared with a traditional tool (i.e., tables).

2. **Representative humanoid glyphs are insightful and need not be intricate to be effective.** Glyphs representing the basic shape of humans—and the variability in this shape across a population—were found to be a useful representation. Participants preferred glyphs in ordered charts as opposed to glyphs in relational scatter graphs.

3. **Appeal to designers’ pre-existing visual knowledge when possible.** Designers generally responded best when the presentation of information capitalized on a conventional format. For instance, scatter plots with color-coded accommodation were found to be well-understood and preferred by participants. However, this guideline ought not preclude the development of new types of visualizations, such as glyphs. When possible, new types of visualizations should use conventions.

4. **Follow the proximity compatibility principle when constructing representations with multiple views.** Small multiples were found to be an effective multiple-view technique. Histograms and probability density functions—common representations of the variation in body size—did not perform well as a communication tool when paired with other representations. This is likely a result of their violation of the proximity compatibility principle.

5. **Consider the purpose for the plot.** Two purposes for multivariate plots are considered in Chapter VI: the display of variability in a population, and displays meant to be used to recommend design changes. In the study, small multiples were not
found to be preferred for making design recommendations, but were preferred for displaying variability. Similarly, glyphs in graphs were not favored for the purpose of description but were more favored for communicating several dimensions of variability to recommend design changes.

7.3 Implementation: A prototype mobile app

A prototype for a mobile application that considers several of the recommendations is presented in this section. The intended use of the app is multivariate product design and evaluation, particularly applications for the U.S. Army. Such an app could be useful in implementing the physical accommodation requirements of MIL-STD-1472 (Department of Defense, 1999). ANSUR data form the underlying model for the app. In some ways, the app is an extension of the interface shown in Figure 6.1 and discussed in the first web study in Section 6.1. Several key features are discussed next, followed by a description of the intended functionality of the app.

The prototype app described in this section makes use of the following recommendations described in this chapter:

- The target user population is carefully considered. Target users are assumed to be men and women in the U.S. Army, and so ANSUR data is used as it is the most representative data available for that population.

- The app simultaneously considers multiple dimensions for appropriate multivariate analysis.

- Real-time interactivity is used as a strategy for exploring the data and making design decisions.

- Simple humanoid glyphs are used in an ordered chart as a representation of the variability in the population.

- Scatter plots with color-coded accommodation and small representations showing various body dimensions in the menus are used to appeal to designers’ pre-existing visual knowledge.
Figure 7.1: Prototype app mockups for the main screen and the design screen showing an encoded scatter plot.

Figure 7.1 shows the main screen for the app, called “MVanthro”, which indicates that two main functions of the app are “design” and “evaluation”. In the design mode (Figure 7.1 and 7.2), sliders permit the user to set limits on relevant dimensions in real time and explore the consequences of those limitations. An “anthro picker” feature (Figure 7.2) allows the user to visually select relevant dimensions for inclusion in the design. The user may swipe between a color-coded scatter plot and an ordered chart of color-coded humanoid glyphs.

Figure 7.3 shows the evaluation mode. A user may add various features to be considered in evaluation of a product—in the figures, the product is a tank. Several features are evaluated simultaneously, including hatch dimensions, seat width, and knee clearance. Additional dimensions may be added by touching the “+” button. This brings up a menu (the “feature view”) where the user can sketch the feature and then add the relevant anthropometry by entering the “anthro picker” mode.
In both the design and evaluation modes, accommodation is calculated by a virtual fit method using the underlying ANSUR data. If limitations are set on multiple dimensions, these dimensions are considered simultaneously. For instance, if an anthropometric datapoint is disaccommodated on one measure, it is considered to be disaccommodated on all measures. Therefore, accommodation may be calculated and displayed based on assigned limitations for each feature in the evaluation mode, but overall accommodation is calculated by considering all dimensions or features simultaneously.

A freely available mobile software app such as the prototype shown in the figures would be a simple way of encouraging adoption of proper multivariate analysis. Tailoring its presentation for the two usage scenarios mentioned earlier (design and evaluation) would further enhance the usefulness of the tool for real-world applications. It could also be useful as a learning tool or could be integrated as a companion to text-based standards, such as MIL-STD-1472. It is important that such an app adhere to the recommendations.
set forth in this chapter—including those regarding DfHV best practices and effective displays of human variability.

### 7.4 Limitations and Future work

This work has several limitations. A larger sample size for the syllabus survey, textbook survey, and practitioner surveys would give a more representative sample and would permit statistical analysis of the results. The first web study assessing the effectiveness of two tools for designing for human variability could also be improved by a larger and more experienced sample population. Large variability in the responses of that survey prohibited many statistically significant findings. Future iterations of the second web study assessing different representations of human variability could be improved by incorporating the findings of this dissertation. For instance, future iterations might...
eliminate representations with pairing and include more representations with glyphs to better understand the conditions under which they are useful to designers.

Future work could build upon this dissertation in several ways. First, new guidelines and tools for applying body size data for design should be constructed following the guidance in this chapter and elsewhere in the dissertation. Conversations with designers revealed that they crave tools for visualizing and designing for anthropometry. They also desire reliable and accessible datasets that contain representative anthropometry for a variety of populations. Second, avenues might be pursued for the integration of the recommendations of this thesis in physical ergonomics education. Third, further studies comparing traditional and interactive tools should be conducted to determine if there is a quantifiable improvement in accuracy or accommodation with the use of improved tools (the study in this dissertation was unable to show a statistically significant difference). Fourth, more multivariate representations might be considered to further expand possibilities for visualizing body size data. Finally, the prototype presented in Section 7.3 could be fully developed and tested with designers to assess its value compared to other methods.

As research on body size for design continues and is applied to the creation of new tools and guidelines for designers, products and environments that we use everyday will fit better, cost less, and bring greater satisfaction.
TABLE A.1: IRB protocol ID, PI, title, and expiry date for the applications supporting the dissertation.

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APPENDIX B

ADDITIONAL INFORMATION FOR THE SYLLABUS SURVEY

Information about college courses was gathered via an internet search and email requests. The following email was sent to 59 instructors at universities in the United States in January and February, 2012:

Professor [NAME],

My name is Chris Garneau and I am a Ph.D. student at Penn State University. As part of my dissertation, I am gathering information about college courses that include some discussion of physical human factors (e.g., work design, anthropometry, etc.) and/or universal design. According to my research, you specialize in [RESEARCH AREA], and I am wondering if you could provide syllabi for any related courses you teach. I am mainly interested in the course outline along with the name of the textbook or other resources used in the class. Any help you could provide would be appreciated.

Thank you.

Table B.1 lists the 18 universities with a usable or relevant syllabus that were included in the study, along with the number of courses considered for each university.
Table B.1: Universities for which courses were considered with usable/relevant syllabi.

<table>
<thead>
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<tr>
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<td>Georgia Tech</td>
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<td>University of Iowa</td>
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<tr>
<td>University of Miami</td>
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<tr>
<td>University of Michigan</td>
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<td>Oregon State</td>
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<td>San Jose State</td>
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<td>Texas A&amp;M</td>
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Two IRB applications were filed with the Penn State Office of Research Protections for the use of human participants for research for the U.S. and Ireland surveys (see Appendix A). Both studies were determined to be “exempt” by the IRB. The next two sections describe the informed consent and survey question instruments for the two surveys. The two surveys had minor but unsubstantial differences in the questions presented.

C.1 Informed consent

A brief description of the research and survey protocol was read aloud to the participants prior to beginning the study, as follows. The participant could choose to participate or decline to participate after the reading.

My research: Generally, I’m interested in how products and environments are designed for people in terms of their size and shape. My research is geared toward understanding how practical design tools may be improved to better account for the variability in the size of users. For instance, I have proposed interactive software tools and ways of better showing multiple dimensions of variability in figures and graphs for decision making.

Purpose: The purpose of this interview is to better understand how designing for body size and shape is practiced in industry, with the goal of informing new tools and guidelines for design.
IRB: This study has received IRB approval at Penn State and is being conducted for research purposes. I will ask a series of questions to assess the design process at your organization in this study. Your participation is voluntary, you may end your participation at any time, and you may choose not to answer any specific questions.

Recording: Unless you object, I will record our interview to aid interpretation of the data later. The recording will then be deleted. At no point will specific statements be attributed to those that made them.

Interview Questions: I’ve prepared several questions to motivate our conversation, but feel free to elaborate about your design process as you wish. I have planned about 20 to 30 minutes for discussion. So that I can plan appropriately, will this amount of time work for you?

C.2 Survey questions

There were five sections of questions asked in both surveys, beginning with background and experience (A), general design (B), procurement (C), universal design (D), and purchase or design for persons with disabilities (E). The Irish survey had an additional section (F) that assessed three prototype design tools, which are shown at the end of this section. Each of these sections are presented next as they were read to participants. “Qualifying questions” determined whether or not each section was relevant to the participant, and the section was presented to them only if they answered in the affirmative. “Key points” highlight the purpose for many of the questions.

Background and experience (A)

A1. Who is your employer/organization? [This generally did not require a response since it was known in advance.]

A1’. What does your organization do? [Required for some of the Irish interviews.]

A2. What is your role in the organization?
A3. Are you familiar with designing for the body size and shape of users of products, or universal design?

A3’. How long have you been involved with physical ergonomics?

A4. Do you have education in human factors/ergonomics? If “yes”, did it prepare you for your job?

General design (B)

Qualifying Question

B0. Have you or your organization solved design problems involving body size and shape? [This generally did not require a response depending on what was known about the participant in advance.]

Key Points

• How does the participant approach designing for body size and shape?

• Where do they get their data and have they had trouble finding anthropometry?

• What tools are favored by the participant? How do they view DHM?

• What challenges has the participant encountered in accounting for body size and shape?

• What suggestions do they have for improvement in this area?

B1. What is the typical design goal at your organization? For instance, design for the mean, design for extremes, design for 90%, etc.

B2. Briefly describe the steps in place at your organization to solve design problems involving anthropometry.

B3. What sources of anthropometric data are used at your organization (e.g., NHANES, ANSUR, etc.)?

B4. Has your organization ever had trouble finding the anthropometric data needed to solve a design problem involving anthropometry? If “yes”, how
was the problem solved? [Participants usually elaborated in question B3–only asked if necessary.]

B5. Has your organization used computer-aided design tools to solve design problems involving anthropometry (e.g., DHM software such as Jack or CATIA Human)?

B6. Does your organization make use of user experiments in the design of products? Where in the design process are they used?

B7. What type of supporting evidence for making design decisions has your organization found to be most effective? For instance, DHM renderings, statistical analysis, user feedback, etc.

B8. Are there any major challenges you have encountered when solving design problems involving body size and shape?

B9. Given unlimited resources, how might you solve the problems you have encountered?

**Procurement (C)**

**Qualifying Question**

C0. Have you purchased/procured products for an organization that are specifically designed to account for different sizes of users? Examples of such products include chairs, office furniture, etc.

**Key Points**

- What products has the participant procured and what features are important to them?
- Where does the participant view human interaction/comfort in their assessment of features?
- Have they ever analytically determined the size of users of their products that need to be accommodated?
- What problems may be commonly encountered in procurement?
C0’. What is the size of the organization?

C0”. What products have you been involved with procuring? What quantity of items are typically purchased at a time?

C1. Briefly describe the steps you use to evaluate products on the market for purchase.

C2. What factors are generally most important to you?

C3. What sources of data do you use to assess the product (e.g., manufacturer catalogs, website product pages, in-person evaluations, etc.)?

C4. On a scale of 1-5, how would you rate fit and comfort of future users in terms of importance among all factors that you have to consider?

C5. Have you ever performed any assessment of the sizes of the people you are purchasing for? If “yes”, how?

C6. Have you ever had trouble finding enough data to adequately assess the product with respect to the population for which you are purchasing? If “yes”, how did you make your decision?

C7. On average, how much time would you require to assess products on the market before making a decision about which one to purchase?

C8. When making a purchase decision, are there common problems or factors that slow or confound the decision?

C9. How do you mitigate those problems/factors?

Universal design (D)

Qualifying Question

D0. Have you heard of “universal design”?

Key Points

- How does the participant regard “universal design”?
- If applicable, how does the participant practice it?
• How does the participant contrast universal design with designing for disabilities?

D0'. Do you practice universal design regularly?

D1. Do you reference principles of universal design? If “yes”, from where? If “yes”, have you implemented them? If “yes”, do you find them useful?

D2. Why do you practice or strive for universal design?

D3. How do you practice universal design? Do you use any other guidelines for universal design?

D4. How do you see universal design as being distinct from designing for people with disabilities?

D5. Are there any challenges your organization has encountered when designing products with “universal design” as a goal? Have you overcome them?

Purchase or design for persons with disabilities (E)

Qualifying Question

E0. Have you designed/purchased products for people with disabilities?

Key Points

• How does the participant view designing for disabilities? What methods are used?

E1. What disabilities have been considered for the product(s) your organization has designed/purchased?

E2. How do you prefer to account for people with disabilities? For instance, do you make sure the same product fits people with and without disabilities, purchase a standard but separate product designed for people with disabilities, or specify a custom designed product?
E3. Are there any challenges your organization has encountered when designing products for disabled people? Have you overcome them?

**Tool assessment**

See Figures C.1, C.2, and C.3, which show the three prototype tools presented to participants.

We are interested in what kinds of tools would most help you to consider the variability in body size and shape as you do your work. We have created three prototypes for you to consider. We would like you to rank them from most to least favorite. You are also welcome to provide any other feedback you would like to. **Please understand that these are not the actual tools—just representations of the kinds of things that some people have found helpful.**

**Conclusion**

Are there any other topics or observations you would like to talk about with respect to designing for user body size and shape?
Universal Design: Data for Considering Body Size and Shape

Other Resources
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Sed blandit viverra purus, vitae porttitor massa tempor et. Integer vel lacus mauris, ut hendrerit nisl.

Maecenas non nunc in risus bibendum viverra. Mauris imperdiet quam pharetra ligula scelerisque et tempus quam vestibulum.

This primer would highlight data and resources for considering the body size and shape of target user populations.

Figure C.1: Template tool prototype presented to Irish survey participants
These web-based tools would allow users to interact with data representing the body size and shape of their target user populations.

Figure C.2: Web tool prototype presented to Irish survey participants
**Universal Design:** Strategies for Considering Body Size and Shape

**Variability:** People come in a wide range of sizes and shapes.

**Preference:** Two people with the same size and shape don’t interact with a design in the same way.

**Boundaries:** Consider the full range of body size and shape in the target user population.

**Data:** When possible, collect data from the potential target user population interacting with a prototype.

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**Process:** The most successful universal designs are a re-imagining of the problem, not a refinement of an existing design.

**Anecdotes:** A design that works for you may not work for everyone else.

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**Interaction:** Consider accommodation on multiple measures simultaneously.

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**Other Resources**
- [www.nda.ie](http://www.nda.ie)
- [www.dfhv.org](http://www.dfhv.org)
- [www.iso.org](http://www.iso.org)

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Figure C.3: Guidelines tool prototype presented to Irish survey participants
BIBLIOGRAPHY


Christopher Garneau received his Bachelor of Science from the Pennsylvania State University in 2007 with distinction and honors in Mechanical Engineering. He received his Master of Science in 2009 and his Doctor of Philosophy in 2012, both from Penn State in Mechanical Engineering.

In 2006, he joined the OPEN Design Lab at Penn State and began research in Design for Human Variability, completing his undergraduate honors thesis entitled “A Comparison of Methodologies for Designing for Human Variability”. In 2007, he was awarded the Dr. John P. Karidis Department Head’s Award for Research Achievement in Mechanical Engineering. In 2009, he was awarded the National Defense Education Program’s Science, Mathematics, and Research for Transformation (SMART) Scholarship, which funded a large portion of his master’s and doctoral research. In 2009, he also completed his master’s thesis, entitled “Investigation of Accommodation for Products Designed for Human Variability”. In 2012, he completed his doctoral dissertation, entitled “Techniques, Tools, and Representations for Solving Design Problems Considering Anthropometry”.

Selected publications


*Won the Ford Best Paper Award in the Design Automation Committee*