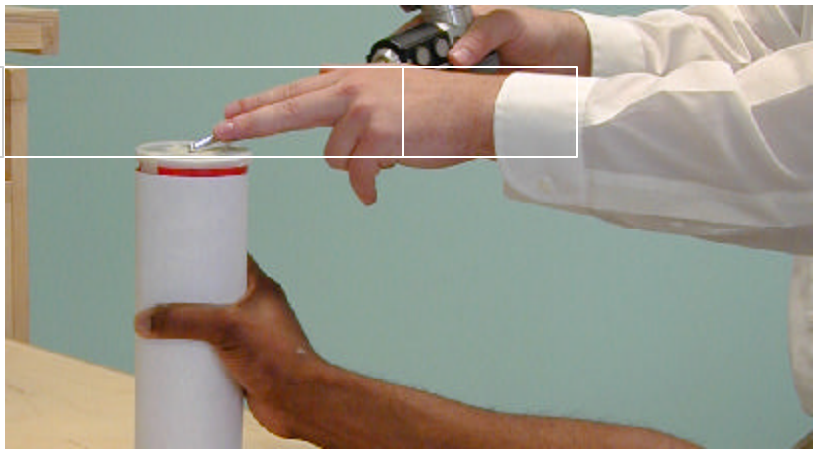
Technical Reports

The Anthropometrics of Disability

Prepared for the U.S. Access Board

Design professionals, consumver advocates and government officials concerned with accessible design and universal design are seeking more reliable data on anthropometrics in a form that they can use more effectively.



Rehabilitation Engineering Research Center on Universal Design

School of Architecture and Planning
University at Buffalo
The State University of New York
Buffalo, NY 14214-3087

The Anthropometrics of Disability: An International Workshop

Version 1.0

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Authors:

Edward Steinfeld
James Lenker
Victor Paquet

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This report is available on the World Wide Web:
http://www.ap.buffalo.edu/rercud

TABLE OF CONTENTS

PREFACE

Anthropometry of people with disabilities is receiving an increasing amount of attention. This Workshop brought together about 40 invited experts from many fields to share information and ideas and to discuss the state of the art in this cross-disciplinary area of knowledge. The goal was to generate new ideas and approaches about data collection, analysis, computer modeling and effective use of anthropometric data in the design of environments and products. An important long-range objective was to identify ways to improve the knowledge bases used in accessibility codes so that they can more accurately reflect the functional abilities and needs of people with disabilities.

Proceedings were prepared for use in the Workshop. This document is intended to summarize both the papers and the discussion that occurred among those present. More formal publications of the full papers and versions of this document are planned.

We wish to personally thank our Co-Organizer, the RERC on Ergonomic Solutions for Employment, our staff who helped to organize the Workshop, and all the Participants who contributed papers and participated in the discussions. In particular, thank you to Lois Thibault of the U.S. Access Board and William Peterson of NIDRR for identifying the need for this event and providing the financial support necessary to make it happen.

Edward Steinfeld, Arch. D.
Director
RERC on Universal Design at Buffalo

DISCLAIMER

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INTRODUCTION

BACKGROUND

"The Anthropometrics of Disability: An International Workshop" was a three-day conference held in Buffalo, NY between May 31 and June 2, 2001. It was attended by about 40 invited participants and featured 20 presentations by researchers and practitioners from around the world who are experts in the areas field of anthropometry and anthropometric issues related to people with disabilities.

The broad underlying purpose for this workshop was captured in the forward to the conference proceedings:

Design professionals, consumer advocates and government officials concerned with accessible design and universal design are seeking more reliable data on anthropometrics in a form that they can use more effectively. Rehabilitation practitioners are looking for new approaches to measuring people with disabilities in order to fit them with seating systems, wheelchairs and other assistive devices. In the wheeled mobility community, researchers, manufacturers and designers are working on international standards for wheelchairs and other related products. Anthropometric data is a key piece of information for that work. In the field of ergonomics, researchers and practitioners need better data to implement interventions in the workplace, vehicles and other settings.

The format of the workshop was a series of paper presentation and discussion sessions. Papers were prepared prior to the Workshop and distributed to participants in printed form. Presentations were timed to insure that about 50% of the time available would be devoted to discussion. All participants submitted written recommendations based on the discussion at each paper session. A final summary discussion was also held to identify key priorities and develop an agenda for future work.

This report is designed to summarize the papers, discussion and recommendations and to communicate it to a diverse audience. To make this report more accessible to the lay reader, a brief overview of contemporary anthropometry is provided. The first section in the main body of the report includes short summaries of the papers and the key points presented in every paper session. Next, we summarize the discussion and recommendations made by participants to advance the field. The last section, the Executive Summary, provides an overview of the entire workshop, presents a proposed agenda for action to follow through with many of the recommendations and identifies specific implications for the two sponsors, the U.S. Access Board and the National Institute of Disability and Rehabilitation Research.

The entire report was designed to provide information as concisely as possible, given the complexity of the topic and variety of viewpoints represented. For those not interested in the details and technical issues, we recommend reading the remainder of the Introduction and then skipping to the Executive Summary. A volume of proceedings has also been produced for those who want to obtain the full text of the papers presented. This document is available for download on the website of the RERC on Universal Design at Buffalo.
(http://www.ap.buffalo.edu/rercud/).

The Workshop was underwritten by the US Access Board, with generous support from the National Institute on Disability and Rehabilitation Research through the Rehabilitation Engineering Research Center on Universal Design at Buffalo and the Rehabilitation Engineering Research Center on Workplace Ergonomics. We thank all the participants for the effort they put into their papers, their enthusiasm and interest at the Workshop and their interest in expanding this effort with other activities in the future.

UNDERSTANDING ANTHROPOMETRY

Anthropometry is the measurement and analysis of body characteristics, including stature, sizes of body parts and the space in which the body functions, e.g. reach limits and clearances for movement. Anthropometry is important for a variety of professional disciplines. It is used extensively in product design, particularly when usability and safety require a close fit between people and their environment. For example, detailed anthropometric studies should be completed in automobile design to make sure that people with a range of statures can have an adequate field of view through windows and mirrors, reach the pedals and hand controls, fit comfortably in the seats and not be exposed to avoidable safety risks in collisions. In architectural and interior design, anthropometry is the basis for many code requirements including those related to accessibility and fire safety. For example, the width of wheelchairs and their occupants is a key determinant of minimum clearances and spaces for reserved seating. In the rehabilitation fields, anthropometry is very important for design of assistive technology. It comes into play in design of mass produced AT as well as in the custom fabrication of adaptive equipment. Because of the large variability in body and ability characteristics of many people with disabilities, the anthropometry of disability poses some major challenges and the need for departures from conventional practices.

Anthropometry is, at first glance, a relatively simple scientific endeavor. However, when it is better understood, like all science, it has many complexities. For example, one of the most difficult problems is identifying where to take measurements of body parts. The first step in this process is defining landmarks on the human body that can be reliably identified by data collection personnel. Variations in selection of landmarks can make a significant difference in results between studies, which challenge those who must interpret the information when making design decisions or decisions about design standards for products or environments. What bony protuberance does one use to mark the location of the shoulder joint? How do you estimate the position of internal points like the hip socket from measurements made on the surface of the body? How do you measure soft body tissue that deforms

when pressure is applied to it like the posterior? These are not easy problems to solve.

There are a great many other issues that add to the complexity of anthropometry and influence the validity and accuracy of this work. Some include:

- What measurements should be taken
- What are the most accurate and efficient measurement methods
- Posture to be used when taking measurements
- Who to select for measurement when everyone in a target population cannot be measured
- How many people are needed to represent the target population
- How to recruit participants including how much to pay them and how to get them to the research site
- How to measure sensitive parts of the body
- What type(s) of clothing should be worn during measurement

Although different terms are used, there are two main types of anthropometry:

Structural anthropometry (often called “static anthropometry”) – measurement of the body at rest including overall measurements like total stature and weight, measurements of links or circumferences like wrist to elbow, knee to hip, circumference of head and measurement of specific landmarks in reference to some other point, like the floor, e.g. eye height. Static anthropometry includes the measurement of assistive devices like canes and wheelchairs either alone or in relationship to the body.

Functional anthropometry (often called “dynamic anthropometry”) – measurement of the body in motion like the reach envelope of seated work, the movement of body parts in relationship to one another or the

space required to turn a wheelchair. Functional anthropometry includes the measurement of assistive devices or other objects used by people as they move. It also includes measures of strength (e.g., grip or pull strength) that depend on the characteristics of a task (e.g., direction in which something is pulled or length of time that force must be held).

Today there is an increasing emphasis on functional anthropometry because it has been established that structural measurements alone cannot fully predict human performance in real world settings where the body is usually in motion or under stress of some sort. This has added another level of complexity to anthropometry because free, or unloaded, movement is not always sufficient to capture the nature of performance in real world tasks. In a great number of tasks, we lift weight and apply force to objects and world around us, sometimes in complex ways. Even in free movement like walking or seemingly static conditions like standing or sitting for long periods of time, understanding the forces on joints and tissue may provide new information leading to improved safety, increased comfort and increased independence. Human movement analysis, or kinematics, and the study of forces on the body, or kinetics, need to be integrated with anthropometry to obtain a full understanding of human performance in functional tasks.

SUMMARY OF PAPERS

The 20 papers addressed topics in 7 related areas:

- **Overview and Summary of Needs** – the big picture of anthropometry and its relationship to design

- **Structural Anthropometry and Reach Capabilities** – measurements of body size and body parts including consideration of clothing and assistive technology used by an individual (e.g. wheelchairs)

- **Functional Anthropometry** – measurement of the body in motion or strength as used in performing everyday activities

- **Human Modeling Based on Anthropometric Data** – computer modeling of the human body and its utilization of anthropometric databases

- **Sampling** – methods and approaches for selecting people to participate in anthropometric surveys

- **Design approaches** – methods for utilization of anthropometric data in design

- **New Directions and Alternative Methods** – emerging research methods that could provide useful information for improving our knowledge of anthropometry and its relationship to life with a disability

The papers were presented in groups of 2-4, with each group relating to one of the 7 topical areas. The presentations were immediately followed by discussion. The summaries below describe the content of the papers and the important points made by the authors.

1. OVERVIEWS

Four papers provided an overview of the major issues that need to be addressed in the field of anthropometry and disability. These papers demonstrated the complex nature of anthropometry and the gap that exists between the need for knowledge and accurate reliable databases.

Lois Thibault provided the perspective of a government administrator who needs anthropometric data to establish policies and standards for design of the built environment. John Roebuck summarized needs for development of accurate and comprehensive static anthropometric measurement methods as well as computer-based models. He identified many of the unique difficulties of this work with populations that have disabilities. J. Mark Porter described approaches to using human modeling in design and suggested that such models be used to create models of individuals rather than using aggregated summaries of isolated anthropometric variables that are more difficult for designers to use. Doug Hobson described efforts to develop standardized postural descriptions for wheelchair users and outlined the benefits of standardization in measurement methods.

Summary of key points:

- Available databases are not providing the information that policy makers and designers need in a form that is easy to use.
- Conventional anthropometry is not adequate for improving our knowledge of the anthropometrics of disability.
- Computer human modeling offers great promise in helping to improve our knowledge as well as providing information in a form that designers and policy makers can utilize more readily.
- Task-based models of individual people with disabilities performing specific tasks could be a very useful resource in the absence of comprehensive human models based on data collected from large samples.

- Standardization in measurement approaches can provide significant benefits by providing a common ground for policy makers, researchers, rehabilitation practitioners, computer modelers, code developers and designers.

- Contemporary issues in the regulation of accessibility emphasize cognitive issues, aging and usability of information technology.

2. STRUCTURAL ANTHROPOMETRY & REACH

This set of papers focused on methods used in anthropometric studies of body dimensions and reaching abilities. The papers described the variety of approaches currently in use and the key issues that contemporary researchers are investigating.

Ewa Nowak reviewed the two basic methods by which arm reach zones have been determined historically and evaluated the relative merits of these two methods with respect to capturing information on people with disabilities. Johan Molenbroek and A.I.M Voorbij compared four methods for measurement of structural anthropometric dimensions and discussed the viability of each for measurement of people with disabilities. Victor Paquet, David Feathers and James Lenker described the development of new approaches to collection of structural anthropometric data including techniques to accommodate non-standard postures, the effects of clothing on measurement accuracy, and the reliability of a new, three dimensional digital-based measurement tool. John Kozey and Biman Das described a tool used to measure normal and maximum reach envelope for adult wheelchair users using a system of potentiometers with automated data collection. They also collected and compared data from able bodied and disabled individuals.

Summary of important points:

- We cannot rely on data from able-bodied people as a substitute for data on people with disabilities.

- Developing computational techniques to substitute for direct measurements of all key body landmarks could reduce the difficulty of research on static anthropometry.

- Computational approaches sacrifice an understanding of the natural dynamics of body function and require validation with actual measurements before one can rely on them.

- Digitally based data collection tools can be used to obtain accurate and reliable measurements in three dimensions, a major advantage over manual methods that only provide information about the magnitude of a dimension or the two dimensional coordinates of a limited number of body points

- Wheelchairs and clothing obscure body dimension data when using visually based methods like scanning, photography and photo-steriogrammetry.

3. FUNCTIONAL ANTHROPOMETRY

These papers emphasize the importance of understanding the relationship between biomechanics and anthropometrics. Strength is a key variable in the ability to complete different functions. This group of papers also identified the importance of wheeled mobility method in using the environment.

Gerald Weisman discussed the need for systematic studies of strength, in its various dimensions, and suggested the need to study the correlation between strength and anthropometrics in the accomplishment of activities of daily living. Alicia Koontz and Rory Cooper described the results of various studies on the biomechanics of wheelchair propulsion, relating the importance of biomechanics to injury prevention and safety for wheelchair users. Laurie Ringaert and her associates summarized a study on functional mobility for users of powered mobility devices, including scooters and power wheelchairs. This is one of the few studies that examined the relationship of anthropometrics, type of mobility device, and functional task completion as constrained or abetted by the environment. Don Chaffin and his associates described research that is

seeking to extend an existing computer model that describes the interplay between trunk, shoulder and upper extremity movements during lifting tasks to the population of people with disabilities, as well as how different lift characteristics affect balance.

Summary of important points:

- Strength plays an important role in everyday life yet is not addressed sufficiently in current accessibility standards.

- Studies of wheelchair propulsion methods and reaching tasks are developing methods for integrating biomechanics and anthropometric variables.

- Computer modeling studies of wheelchair users are uncovering a detailed understanding of the dynamics of upper body and trunk function.

- Methods have been developed that provide precise simultaneous data collection on both anthropometric and biomechanic variables over time.

- The current research has utilized small samples and needs to be expanded to understand the impact of variable such as age, disability, stature and other factors.

- New wheelchair technology, both in manual and powered devices, is resulting in different performance characteristics and new environmental needs.

- Changes in codes and standards may be needed to address trends in the use of wheeled mobility devices.

- An important issue to be addressed in revising codes and standards is to what extent the design of wheeled mobility products should drive standards and to what extent standards should drive design of those products, e.g. should built environments be designed to accommodate scooters, which were

originally designed for outdoor use but are now increasingly used indoors?

5. SAMPLING

Two papers were presented on sampling for anthropometric studies of people with disabilities.

Some background is important in understanding these issues. Historically, anthropometric data has mostly come from military samples yet research shows that there are real differences compared to the civilian population. Thus sampling from the broader population is critical to developing databases that are useful for the design of the everyday environment. Conventional sampling strategies select study participants using proportionate strategies, e.g. if African Americans constitute 20% of the population, then 20% of the sample will be made up of African Americans. Typically, design based on anthropometrics tries to accommodate 95% of the target population but most people with severe disabilities fall outside that level when proportionate sampling schemes of the total population are used. This means that disability will be very underrepresented in conventional anthropometric studies. Some studies purposely exclude people with disabilities and older people to keep the results unaffected by "outlying cases" or people who have widely divergent abilities and characteristics.

Bruce Bradtmiller reviewed the basic issues of sampling in anthropometric research. He described the key problems in sampling related to disability and outlined the related challenges of future research. James Lenker and Victor Paquet presented two alternatives to proportionate sampling strategies for people with disabilities and compared their benefits and limitations.

Summary of important points:

- Proportionate sampling does not provide the best results when the anthropometric characteristics of groups in the population are very different, e.g. since there are many more people with arthritis than people with Cerebral Palsy, data based on a proportionate sample of people with disabilities framed by cause

of disability will not represent the needs of people with CP very well.

- Independent sampling of groups can help to identify and compare the characteristics of people from small groups; however, it then becomes difficult to define the characteristics of the entire target population, i.e. there will be several 95th percentile values.

- In anthropometry of people with disabilities, we should re-evaluate the confidence level typically used in determining the size of samples (95%) because of the high cost of recruitment and time in data collection; there is no magic in the 95% target.

- For people with disabilities, using a lower confidence level may be reasonable because one can assume that many individuals will need custom design solutions.

- Sampling frames based on cause/source of disability do not reflect the functional variation within any category and the dynamic nature of disability over time.

- Sampling on type of mobility aid used would represent the variation in functional ability and be relatively easy to implement.

- Stratification on type of mobility aid used is complicated by people who use more than one device or who may use a device only part of the time or in certain limited settings.

- Sampling based on functional independence in activities of daily living could be implemented with well established scales; this would make it easier to apply findings in design for diverse populations and would be consistent with the universal design perspective–a continuum of needs based on functional ability.

- Stratification based on functional independence requires screening participants prior to selection using trained professionals.

- Defining functional independence is difficult since it is mediated by the environment in which a person lives.

6. INTEGRATING RESEARCH WITH DESIGN

Papers on this subject addressed several different issues.

Edward Steinfeld described a full-scale approach to physical modeling in which functional abilities are observed as users complete tasks in an environment that has realistic dimensions, tools and fixtures. Traces of performance can then be mapped onto the environment to determine what is usable by the study group and to understand their preferences. Such information eliminates the need for the designer to interpret data from anthropometric databases or manipulate manikins.

Matt Reed compared the two traditional approaches to the development of computer-based tools for design, the human figure model and task-oriented model, in terms of usability in design activities. The former is based on the development of a virtual human manikin connected to a database of anthropometric data. The figure can be manipulated by adjusting it to body dimensions in standard postures, moving limbs using joint range of motion predictions and putting it into task specific postures. Task oriented models on the other hand, use databases and statistical techniques to directly predict an outcome variable (e.g. range of visual field for the driver of an automobile).

Joakim Eriksson described a prototype 3-D computer manikin that is integrated with a computer aided design system. The prototype uses a non-proprietary, open format, based on common spreadsheet software that would potentially allow so-called "open-source" development by those conducting human modeling research. Data from any study, if organized into the proper format, could be used to size the manikin.

Summary of important points:

- Designers need direct visualization of how anthropometry affects performance, e.g. reach envelopes, field of vision, etc.

- Typical anthropometric data provides generalized information on people rather than information specific to a particular product or environment under development.

- Full-scale modeling provides more design-specific information than conventional anthropometry and can provide information on the interaction of person and environment that is easy to visualize.

- Human figure modeling provides an excellent platform to make research data available and accessible to a broad array of applications.

- Task oriented models can be implemented within the user interface of figure models to provide task specific analyses and graphical output that is comprehensible to designers.

- Combined physical modeling and CAD tools can provide a vehicle for integrating data from anthropometric studies easily into design tasks.

- An open source approach would allow researchers from many fields to use the same modeling tool and bring their data to the design workstation.

- A long-range goal is the development of computer models that reliably predict behavior in situations that have not yet been studied in anthropometric research.

7. NEW RESEARCH DIRECTIONS

Three papers focused on experiences with new research methods that could benefit the development of the anthropometry of disability. Jon Sanford described how a survey research study on user needs and preferences helped to evaluate the effectiveness of codes and standards in meeting the needs of a specific population. Sharon Hewner described how ethnographic research methods can be used to developed user-centered scales for evaluating function in the environment. James Llinas

gave an overview of multi-source data fusion as a method for meaningful aggregation and analysis of data that have disparate form and characteristics and could potentially be applied to anthropometrics data.

Summary of key points:

- Anthropometric studies in themselves do not measure effectiveness; additional research techniques are needed to insure that the recommendations that derive from anthropometry are actually improving independence and safety.

- Outcome measures need to be defined to measure effectiveness.

- Ethnographic methods can be useful tools for defining successful adaptation to the environment from the user's perspective.

- New techniques allow the construction of reliable outcome scales from ethnographic data.

- Survey research can be a useful approach for identifying differences in use of environments and products related to social factors like age.

- Studying anthropometrics of caregiving is critical to meeting the needs of an aging population.

- Existing code requirements may be restricting our ability to deliver environments that will facility independence and safety for the older population.

- Data fusion allows the automated analysis of data from multiple sources. It could greatly simplify data analysis from functional anthropometric studies.

- New methods for collecting streams of data from multiple sources are needed to implement data fusion approaches.

- Data fusion may be useful in interpreting and mining data from a diverse set of databases.

SUMMARY OF DISCUSSION & RECOMMENDATIONS

The papers were meant as the point of departure for discussion of the issues surrounding this type of research and generating recommendations. Each presenter advanced specific points of view and recommendations. From there, all participants joined in to discuss the themes, facilitated by a session moderator. Discussion occurred after each group of papers was presented so that it usually addressed issues common to each set and often expanded on themes established earlier in previous sessions. At each session of the workshop, about half the time available was devoted to discussion. Two different note takers recorded the points made. In addition to the verbal discussion, participants were asked to submit written recommendations for research, practice and policy for each discussion period. They wrote their recommendations during or immediately after the discussion on the papers. About 130 individual recommendations were submitted. Clearly, participants took that task very seriously. At the end of the Workshop, a wrap up session focused on a summary and final discussion.

In order to summarize the main points of the discussion and the recommendations in a concise and meaningful way, we used content analysis to group them into 10 main themes:

1. Increasing standardization in methods
2. Increasing use of functional approaches to research
3. Better organization of knowledge
4. Identifying research priorities
5. Developing computer simulation models
6. Incorporation behavioral and social factors
7. Improving sampling
8. Improving cost effectiveness of research
9. Improving data collection methods
10. Increasing communications and dialogue

Each one of these themes will be discussed below by summarizing the discussion related to them, reporting specific recommendations and elaborating on the recommendations with further observations.

1. INCREASING STANDARDIZATION AND CONSENSUS IN RESEARCH AND PRACTICE

Much discussion focused on the limitations of previous research. In older studies, the methods used were so different from study to study that it is difficult to interpret or utilize the results. In particular, since most previous studies used small samples, the differences in methods make it impossible to combine findings to create a database that allows a higher level of generalizability. By standardizing methods, the results of small or focused studies could be pooled to establish larger databases. Moreover, it would be possible to compare the results of studies completed with different populations, e.g., different disabilities, different age groups, etc. Other recommendations focused on the limitations or even undesirability of using standard postures and clothing for this group. Unorthodox ways of standardizing posture and clothing may need to be devised. Finally, some recommendations focused on

With respect to improving standardization, specific recommendations include:

- Develop an ISO standard on how to measure people with disabilities. This standard should identify which body landmarks should be measured and define each landmark. It could also establish guidelines on how to measure people, e.g. use of standard, “normal” or “resting” postures, use of restraints or body bracing during reaching trials, use of two or one hand for measuring reach limits, etc. The definitions should be easy to understand and measure with the tools available. It was also noted that encouraging policies based on an ISO process is problematic because of the difficulty in getting everyone to agree. There may also be many culturally based differences, especially between developed and developing societies. Before starting an ISO process, it was recommended that a good document with terminology and proposed standards be developed first.

- Determine the target population for anthropometric studies through a collaboration of researchers and government funding institutions. Researchers need to have some sense of the target population for standards and policy in order to establish sampling plans. By defining a profile for samples through consensus, researchers will have a better idea of what populations need to be recruited and sponsors will have realistic expectations about the generalizability of results for the application of data.

- There is a need to develop simple tools to make the measurements, for example, easy to use measurement devices, pre-developed protocols and databases. This will avoid the need to re-invent data collection methodologies and data management systems. The methods developed should be affordable so that many researchers can adopt them rather than just one or two specialized centers. This will facilitate their use in clinical practice as well.

- Government can take the initiative to fund a "meta-database" through which individual studies could be combined.

These recommendations focused on the need to be cautious in standardizing research methods:

- Avoid reliance on so called "standard postures." People with disabilities often cannot maintain a "standard" position or may not be able to hold it for long. It may be desirable to measure people in several positions for each task.

- A standard method for taking clothing into account is needed, especially in functional studies where clothing may affect range of movement. Other problems with this population are that many individuals may not be able to wear "standard" articles of clothing, may be more reluctant to be measured nude or partially nude, and may take a long time to change into clothing provided at the research site.

Several participants suggested the use of standardization to improve the application of anthropometric research to practice. These two recommendations summarize these perspectives:

- Government agencies should strive to develop "performance standards" rather than specification standards for design. Such policies could include requirements or options (e.g. "equivalent facilitation") to use anthropometric and ergonomic tools like computer models in order to accommodate a certain percentage of the target populations. It could also include the development of consensus based testing protocols that can be used for evaluating the accessibility of products.

- Develop a discussion group to standardize the methods in order to tie anthropometric databases to computer aided design (CAD). This could lead to a manual that could be used by researchers and human modelers.

2. INCREASING USE OF FUNCTIONAL APPROACHES TO RESEARCH

The discussion centered on the need to put more emphasis on functional anthropometry than structural anthropometry although the participants recognized the importance of structural anthropometry in order to understand the relationship between body (and assistive device) size and function. While many of the recommendations focused on the general issues of functional anthropometry, there were also a number of very specific recommendations about methodology with a view toward developing research methods that reflect reality more closely.

Recommendations about functional anthropometry in general include:

- Functional anthropometry includes more than simple movement. There is a psychological component. For example, maximum reach may not be reasonable to expect on an everyday basis, especially for tasks that are frequently repeated. An acceptable reach limit for a task would be a more realistic functional approach. This may vary based on the context of the task, e.g.

the frequency at which it has to be done, expectations of others, rewards.

- It is important to develop data for specific tasks and population groups. This includes different reaching tasks, wheelchair maneuvers and viewing tasks like reading a computer screen. It also includes understanding the differences between age groups, impairments, sexes and cultural groups. For example, there may be a need to use alternative landmarks for different disability groups. Another issue is defining reach in terms of one hand, two hands or either. Many people need two hands to accomplish something others can do with one. Should reach envelopes be derived separately for one handed or two handed reach or could preferred reach be used as the basis for measurement?

- The way people with disabilities perform tasks and activities in the real world should be studied, not just laboratory based behavior. Ideally this would come prior to the design of laboratory based research so that results can be more relevant to practice.

- Data collected on limited standardized tasks should be related to a wide range of specific activities. For example, data on two handed lifting of an object could be applied to a variety of tasks like lifting something out of an oven, from a refrigerator, from a table or from a work desk. Identifying generic tasks associated with Activities of Daily Living (ADL) could be used as a basis for task-based functional anthropometry.

- In studies of wheelchair users, it is important to investigate how people actually use a wheel chair in different places and under different conditions. The method of transfer used, for example, may vary based on the characteristics of the environment due to preference and adaptation to constraints. Assisted transfers need to be studied as well as independent transfers.

- The type of wheeled mobility device used plays an important role in functional anthropometry. Studies comparing usability of environments by the same people in different types of devices

could identify limitations due to the type used, e.g. scooters, as well as identify directions for improvement of different types. In interpreting findings, it is important to consider the appropriateness of devices used by individuals and to avoid basing recommendations on technology that is obsolete or ill conceived.

- The impact of pushing practices and rim design should be investigated as part of functional studies of wheelchair maneuvering.

Specific recommendations for methodology include:

- Strength is a critical variable in reaching ability. It is important to understand the relationship of weight of object being moved and strength to task performance.

- Free reach may not be too useful to measure because people are always using or grasping objects while they reach. However, even free reach must overcome gravity so strength always plays a role. This suggests the need to measure the body and body segment mass to understand reach in a biomechanical context.

- Research should take into consideration "functional" reach posture. For example, static and relaxed positions may be more appropriate for measuring functional reach than extended postures. Head movement in functional tasks is often overlooked but it can play an important role, especially if the task involves eye-hand coordination.

- Studies of reaching abilities and grasping tasks for people with disabilities should accommodate different methods of reaching, including two handed reach as well as one handed reach, the use of one hand to brace the other or the use of a wheelchair to stabilize the body while reaching.

- The fact that people may not be fully independent should be recognized in research. When selecting samples or reporting results, independent populations should be separated from dependent populations.

3. BETTER ORGANIZATION OF KNOWLEDGE

Discussion on this theme focused on organizing knowledge with a view toward making it more useable in design practice. Participants were concerned with the organization of the existing knowledge base as well as new knowledge that will be generated by future research. The recommendations include approaches to organizing research data and findings as well as the form of design criteria.

Recommendations included ideas for organizing data for improving our knowledge base and access to research findings:

- Existing technical standards are rigid and incomplete. Performance criteria could be developed for design based on person, environment, tasks and level of assistance to be provided. This approach would be richer and more useful.

- There is a need to review current literature and research as well as past comparisons of existing studies. While Bruce Bradtmiller completed a comparative report, it would be very useful to hold a seminar where the existing work could be discussed further by a broader group of experts that includes designers, human modelers and others.

- A database library should be organized to collect all the data from old and new studies in one place and make it available to others in a consistent and easy to use form. NIST is working on a web-based data-structure for anthropometry which could be a good model on how the government could be involved in setting up a shared database.

- We need to use existing data, best practice information and expert opinion to augment codes and allow exceptions. Organizing data in a form that could be mined for different populations and tasks would help to identify the gaps in our knowledge and frame a research agenda. The Access Board has

begun to do some things like this, e.g. the Children's Guidelines and the Recreation Facilities Guidelines.

- Existing databases should be reanalyzed. For example, the New ANSI Standards Project completed in the late '70's collected data on wheelchair size that was not analyzed in detail. The data was also not analyzed to study age related differences in performance.

- A multi-site initiative using the NIH model would facilitate interdisciplinary perspectives and be useful to evaluate what data would be included in a shared archive or database.

- Other disciplines should be contacted and involved in this area of research. We need to find ways of contacting those groups that would be interested and have something to contribute. One of the most important to involve is the design community to be sure that they will utilize whatever new information is developed.

- Build anthropometric models and automated code checking programs based on anthropometrics into current design tools, e.g. AutoCAD.

- Investigate sociological resources. Perhaps a compilation or bibliography on relevant literature would be a first step.

- Assemble data on accidents involving people who use wheelchairs using an epidemiological approach. Such data would be very useful for understanding the impact of standards and codes in real life.

- There were also several recommendations about how knowledge could be more effectively applied in everyday practice:

- Knowledge from anthropometric research should be integrated into clinical practice in wheelchair design and fitting. Although the emphasis has been on design of the environment and products, research results could improve wheelchair design as well indirectly making the environment more usable.

- Interactive interfaces could be developed to enable non-experts to access and use databases effectively. The AIS system developed at TU Delft is an example. Testing shows that students use it more effectively than data in books.

- A reasoning model for designers should be developed to help them go beyond code requirements. The codes and standards should only be guides. The reasoning model could help designers provide an authoritative rationale for departing from standards (e.g. equivalent facilitation).

- Policy incentives could improve the utilization of knowledge. For example, government purchasing policies could encourage designers to use anthropometric/ergonomic tools as a means to accommodate a given percentage of the population.

- There needs to be more discussion on the most effective way to present and collect anthropometric data in a way that will be useful to designers. This is a major issue of concern among researchers. How can we increase demand for research products? One possibility is to make using anthropometric interesting and entertaining.

Another set of recommendations focused on improving data analysis in research to make use of results more effective:

- Data analysis strategies are needed before large-scale surveys are implemented. Otherwise, the data may not be usable.

- In analysis of data, we should not rely on the normal distribution model. We need to develop new strategies for analysis that take into consideration the great variation in the population of people with disabilities and the fact that there will be small numbers of people in each multidimensional sampling category.

- Averages are meaningless in design for disabilities. Report findings in percentiles and also individual performance. This allows users of the data to determine who is being accommodated and, where the aggregated data is inadequate or

not detailed enough, the individual data can be used in human modeling simulations of individuals performing specific tasks.

- Cumulative normal distributions could be more effective than percentiles for code development because they identify clearly which part of the population is included; however, such an approach implies an assumption of normality, which might not be an accurate way to represent the range of body sizes and abilities of those who have disabilities.

- Explore how static anthropometry could be used to predict baseline functional measures. This would help us adapt static data, which is easier to collect, for application to functional tasks.

- Develop 3-D equivalents of percentiles in order to make it easy to generate recommendations for 3-D data.

4. IDENTIFYING RESEARCH PRIORITIES

Because there is so much work to be done in this area, establishing priorities for research is difficult. There was discussion about how to determine what topics should be studied and also how to go about implementing research on priorities. The specific recommendations were as follows:

- Research priorities should include input from all stakeholder groups: researchers, policy makers, manufacturers and consumers.

- The research community needs to address hot issues in the area of disability, accessibility and universal design. In the U.S. these include aging, people of small stature, employment, communication of information and cognitive impairments. There are many crossover concerns between anthropometrics and these issues.

- It is important to pay attention to those groups that cannot drive the market for research. For example, the growth of the older population has created an increased need for data on the

anthropometry of this group to produce consumer products and environments that meet their needs.

- The priorities of people with disabilities should be identified to avoid studying the wrong issues. For example, consumers may indicate that the problems they have using a shower are related to the curb or the seat, not the size of the shower itself. There is no need to devote significant effort to topics where the end users perceive no serious problems with anthropometric fit. Consumer input will help avoid "fishing surveys," or anthropometric studies that do not address real problems faced by end users.

- People with disabilities should be involved in the design of anthropometric research – its content, methodologies and applications. They are the best group to evaluate what is appropriate and what is relevant.

- Identify topics based on experience in practice. The Access Board should have information on what complaints have been made about meeting the ADAAG. Those items that have caused controversy because people question the anthropometric data behind them would be good items to put at the top of the research agenda. The Department of Justice's Office of Civil Rights would be another good source of information of this kind.

- Information on aging populations is critical for the near future. As the population ages, we will need to put more emphasis on age related differences in anthropometry. A focus on aging would also increase funding opportunities – anthropometry is not just a disability issue.

- The development and adoption of new technology like scooters and non-visual systems for ATM's and ITM's drives a need for new information. It is important to consider the development cycle of technologies. New technologies may evolve rapidly after introduction. For example, scooters were originally designed for outdoor use; now that they are being used indoors, their design may change significantly to accommodate smaller interior spaces. Should the standards reflect the existing designs of scooters or

should the scooters be redesigned to address the constraints of interior spaces? Questions like these have to be a part of the scope when new technologies are the focus of research.

- NIDRR and the Access Board should cooperate more to develop research activities that address specific policy issues. This would insure that research addressed topics related to issues of concern in the field and also help to bring more research funding to the anthropometrics and ergonomics of disability.

5. DEVELOPING COMPUTERIZED HUMAN MODELS

All participants at the workshop seemed united in believing that computer simulation models would advance the cause of anthropometric research and help to improve utilization of findings. Recommendations in this area were directed to the type of models that are needed and how to develop them. There was a general consensus about insuring that simulations were derived from empirical research with the target populations.

Recommendations related to human modeling included:

- Human form models used in CAD systems need to be improved to represent a more diverse population, e.g. age differences, different types of disabilities.

- Develop simulations of real people that can be studied independently as part of design activity, rather than models that are statistical interpretations of data. Thus, instead of models that estimate one set of body dimensions and capabilities from one anthropometric dimension (e.g., stature) to create a 10th percentile or 25th percentile "model", which doesn't truly reflect the characteristics of any individual, instead, designers could select models based directly on the performance data of individual people to test out their designs. This would be a more realistic use of simulation, and would be an extremely powerful design tool if designs could be tested with repeated simulations of different individuals.

- Develop kinematic and biomechanical models to estimate the percentage of the population capable of different tasks. This could be used in policy development. The National Institute on Occupational Safety and Health has established a precedent in using computer models to implement policy. Such policies would require testing with authorized models to prove anthropometric fit.

- Both "task oriented" and "figure models" should be used simultaneously. They are different types of representations and both can provide useful information. Task oriented models are designed to focus on specific tasks like determining sight lines whereas figure models are general models of the human body that can be applied to a variety of different tasks. Task oriented models are more cost effective to develop because they focus on a limited number of variables but they may not help a designer explore all the important tasks of importance in an environment. Figure models, on the other hand, may include more variables but may not provide enough detail for application to specific tasks. Task oriented models can be developed quickly when there is a critical need for information but they can also be developed in conjunction with figure models to produce a more complete set of tools.

Recommendations related to the construction of models include:

- Modeling should not use overly simplistic representations. Motion capture technologies can be used to measure and model how people really behave.

- Incorporate movement related to perception in modeling tasks that require vision to complete, e.g. pick and place or adjustment tasks. For example, it is not enough to know if people can reach an object because they need to be able to see it as well.

- Exploit computer representations of data that do not require assumptions about the distribution of abilities and body measurements in the actual population. For example, simulations

could use probability functions to generate data for use by models (e.g. Monte Carlo simulations).

- Researchers who collect data need to be collaborating with model developers to insure that the data needed to produce valid models will be available and that the models will be effectively integrated into the designers "desktop." Both groups need to collaborate with CAD software developers to make sure that the specific tools and representations needed in design are at the designer's "desktop."

- Models need to be validated against real world behavior – they must have predictive validity before they can be used with confidence.

6. INCORPORATING BEHAVIORAL AND SOCIAL FACTORS

Several of the participants at the conference argued that social science research methods are needed to understand many anthropometric issues. In particular, such research can help us understand the perspective of people with disabilities, how social and cultural factors influence anthropometrics, and the differences between groups. These specific recommendations were made on how such research could benefit the field:

- Consider the perspectives of people with disabilities. Not only is it important to insure that the critical issues of concern to the population with disabilities are addressed in anthropometric studies, it is also important, given limited resources, to avoid devoting resources those issues that are not perceived to be problematic to the target population. Thus, studies that would uncover priorities for giving research attention to specific issues would be very valuable.

- Anthropometric research should consider the role that social and cultural factors play in successful task performance. This includes understanding the role of age, education, ethnic origin and other

such variables.

- Utilize psychophysical scales in combination with observable measures of performance. Typical outcome measures are complete/incomplete, maximum reach or comfortable reach. More sophisticated measures are needed. Scales that evaluate difficulty, satisfaction, acceptance and other psychological measures can help us to understand how people evaluate demands that the environment makes on human abilities. Special emphasis should be given to the psychological evaluation of effort during manual exertions. This seems to be a major knowledge gap.

- Validate the findings of laboratory studies through field research. This could include the use of 1.) psychophysical methods to rate successful performance and 2.) ethnographic research studies to understand how individuals interpret tasks and decide on the level of performance they will strive to attain. Predictive validity would be strengthened if personal perceptions were studied along with observed performance. Using data fusion methods to handle multiple data inputs like this would help to justify code requirements.

- Set design criteria based on subjective response rather than purely observation of behavior. In particular, it is important to consider acceptable of levels of effort, independence and productivity. Simple ability to complete a task is not sufficient for understanding whether it can be done satisfactorily. Ideally, the criteria for successful performance should be determined by the target population.

- Identify levels of acceptable risk, discomfort and inconvenience to guide policy. We know that people are willing to accept certain levels of risk, inconvenience or discomfort to enjoy certain experiences but we do not know how disability affects such decision-making. In defining the minimum requirements of access where constraints to full access are significant, such as in existing buildings, historic buildings or in natural areas, it would be valuable to know what people with disabilities themselves think

about these factors in the context of different tasks and experiences.

- It should be noted that the last two recommendations are not contradictory. The first is focused on how to establish acceptable levels of accessibility. The second, however, is concerned with cases where the desirable levels may not be possible to achieve or the impact of such levels may be undesirable for other reasons besides usability, e.g. historic integrity, natural resource preservation, etc.

7. IMPROVING SAMPLING

Sampling has clearly been a serious problem in past research. Most previous studies have used small samples, often recruited from easy to obtain population groups, e.g. from clients of clinics or residents of institutions. Much discussion and recommendations focused on how to improve sampling to make sure that research populations were more representative of the population of people who have disabilities and also were large enough from which to make generalizations.

These were the general recommendations made by the group:

- Larger, more comprehensive samples of people with impairments are needed. Samples are needed that include 1000-2000 people. Existing research has not included large enough samples with sufficient diversity to understand the variation across individuals and groups or to insure that findings are representative of the entire population. Sample sizes have been largely determined by the resources available to the investigators. It is critical for funding agencies to recognize the importance of providing adequate resources to recruit larger and more comprehensive samples. Other related solutions include the adoption of standardized methods and advanced training of many research teams to allow data from several samples to be aggregated together for analysis purposes.

- People with disabilities should be included as a matter of course in ergonomics and human factors research. Traditionally, this group has been excluded from such studies because they are considered "outliers" in terms of performance, they may be more expensive to recruit and/or lack of accessibility to the research site or apparatus. The professions involved in human factors research and research sponsors have to be educated to insure that such practices change. Including people with disabilities in general anthropometric research will produce a lot more data on the anthropometrics of disability with only a marginal increase in cost, if any. It is important to note that changing sampling policy also implies changes apparatus and possibly methods. For example, full body scanning may not accommodate people who use wheelchairs because parts of the wheelchairs obscure body parts. Or, a raised platform accessible only by stairs may be used as part of the apparatus.

- All researchers need to clearly document their sampling methods to allow future researchers to utilize the data collected. Many previous studies did an inadequate job of documentation to the point where lots of questions have been raised about the results. Funding agencies can insure that the samples used in research are clearly documented.

- Sample at the extremes, or "tails," of the distribution of abilities. This will insure that the full range of abilities are incorporated in the sample. This refers specifically to samples or sub-samples of people with disabilities. This may require alternatives to methods that require study participants to visit laboratory settings. For example, the RERC on Universal Design at Buffalo has developed methods that can be brought to the individual in order to insure that lack of mobility in the community will not preclude people from being part of the research sample.

- Include a focus on elderly populations. In view of the rapid demographic shift in industrialized societies toward a more mature demographic mix and the rapid increase of older populations in the less developed world, sampling more people of advanced age is critical to meet the information needs of the 21st

Century.

- Include caregivers in anthropometric studies. This will help us to understand how their presence has an impact on space needs and functional requirements. They should be considered part of the "system" under study.

- Recruit samples that are accessible for longitudinal studies. Long-term clients of rehabilitation organizations are valuable targets for anthropometric research because they can be studied over time. Changes related to aging and technology (e.g. wheelchair design), in particular, are likely to make significant differences in both static anthropometry and functional ability.

- In using samples selected from rehabilitation clinics, obtain non-volunteer samples wherever possible because volunteers may have higher levels of motivation and lower levels of impairment than the entire population. This would require instituting universal anthropometric screening for such populations to insure that everyone is included.

- Training is needed to educate researchers and peer reviewers who evaluate research proposals on sampling issues related to disability. This training should include information on the problems of recruitment from populations of people with disabilities. It could also include effective sampling approaches and their uses, recruitment techniques, how to fully document sample construction, threats to validity, the relationship of sampling to the development of hypotheses, how sampling size affects confidence levels, data available for population estimates, relationship to data collection methods and issues related to statistical analysis.

- Peer reviewers for research grants need to be educated to understand the problems of sampling from populations of people with disabilities.

Several recommendations pertained specifically to the anthropometric study of those who use wheelchairs.

- Prototype studies like the one conducted by the RERC on Universal Design at Buffalo will have to be small and limited. The population used should be well documented but it is less important that it be representative. The main goal of prototype studies is to develop reliable and valid methods and models of analysis and documentation. Once methods are proven, the sample can be expanded and others can be trained to collect similar data.

- The sampling strategy used in the development of a prototype database must take into consideration the future broader development of the study. The sampling techniques need to hold up over the long term and mesh as closely as possible with previous research.

- Type of mobility aid used (e.g. manual wheelchair, power wheelchair, scooter, etc.) is a good variable for stratification in a study of wheelchair anthropometrics because it is constant across tasks, can incorporate a wide range of impairments, and the number of users within large populations can be determined quite easily in surveys. It also allows comparison with previous research as long as type of aid was documented. Sampling by impairment group, on the other hand, significantly constrains recruitment because people in many different categories need to be included. Impairment may be defined differently by different individuals, and many people may have multiple impairments, making the reliable stratification by impairment difficult. Moreover, use of wheelchairs varies significantly across impairment group and is related to health status. Stratifying by impairment may overemphasize certain impairment categories and is less useful to designers who tend not to design for a specific impairment group but rather to accommodate users of a particular mobility aide.

- Functional ability, as measured by scales like the Functional Independence Measure (FIM) or the Wheelchair Skills Test can be used to complement type of mobility aid and to evaluate the inclusiveness of the sample. Assessment of functional ability can help to assess whether people with a full range of abilities are being recruited. Theoretically, the range of each sub-sample

based on mobility aid type should approximate a normal curve in functional ability.

Several recommendations were made that related sampling to the utilization of information from research:

- Researchers should collaborate with government funding and policy-making agencies to identify the target populations for different types of research. It is very important to understand that there is not one target population. Each application of data may have a different one, e.g. young or old people, engaged in work or recreation activities, fit or frail, etc. NIDDR and the Access Board should play a leadership role in defining the groups that need to be sampled and insuring the use of uniform approaches. The population of people with disabilities is so diverse that some tacit understanding of who is being served by research is needed in order to develop acceptable sampling plans. Through clinical experience, review of available demographic data and previous research, target groups can be identified based on level of impairment, level of independence and functional limitation. Consideration should be given as to how such target populations should address social factors such as age and sex as well as biological and genetic factors such as extreme stature and ethnic diversity. The target populations should be defined in a manner that allows the application of statistical techniques to existing demographic data in order to establish the generalizability of findings, e.g. confidence level, power estimates.

- Agencies like the Access Board and the U.S. Department of Justice need to specify how many of which population groups must be accommodated by a new design that is covered by access laws and regulations. Without such target, a manufacturer has no guidance or incentive to create compliant products. No matter what they do, there will always be complaints that they didn't accommodate some group or another.

- Develop standards for different population groups, e.g. children, older people, etc. This requires sampling for those specific groups where good reasons exist to assume that there would be great differences in needs and abilities that should be reflected in

products and environments designed for use primarily by these groups.

- Description of samples based on functional ability is useful for developing performance based code requirements. Code requirements can be clearly related to the percentage of the population that is able to perform at a certain level on specific functional measures. The FIM score is very valuable in this regard because of the vast amount of data available on assessments made with the FIM instrument.

8. IMPROVING COST EFFECTIVENESS OF RESEARCH

Many of the Workshop's participants were experienced research administrators. Discussion of research methodology and sampling issues identified the need to study more factors, use larger samples and improve data collection methods. This raised questions about the availability of resources to reach ambitious goals. Representatives of government agencies warned that expecting large increases in funding was probably wishful thinking. So, discussion on the cost of research emphasized strategies to make research more cost effective.

These specific recommendations were made:

- Identify new sources of funding. There are many other Federal agencies that could get involved including the Department of Defense, which has the most money of all Federal agencies. Corporate funding is also a good possibility. Ford and GM, for example, both have initiatives related to aging.

- Research methods should be devised that reduce the cost of data collection. The methods should minimize the amount of time required to collect the necessary data and use a small amount of space. Ideally the participants should not have to keep still, reducing the need for special apparatus and transfer to a special seating system. Most likely, automated methods would be more cost effective if they can achieve an appropriate level of

accuracy.

- Develop a level of accuracy and completeness in measurement that is appropriate for the needs of designers. Some measurement techniques may be accurate enough for collecting data needed for some design tasks while not accurate enough for others. There is no need to spend a lot of money to achieve a level of accuracy and completeness that is not actually needed. For example, accuracy within 1/10th of an inch is not necessary for architectural or interior design. For adaptive equipment design, however, especially when devices are worn on the body for long periods of time, such a level of accuracy may be needed.

- Motion analysis or capture systems is the "gold standard" against which all other measurement techniques are compared. But, motion analysis is very time consuming and expensive. It needs to be used selectively. Innovative methods can be validated against the motion analysis standard.

- Standardize protocols and measurement systems using an affordable approach. This can make measurement of the human body more cost effective for many research teams. The ramping up costs of developing methodology and apparatus are reduced significantly when many researchers share the same protocols, data collection techniques, software and apparatus.

- Institute a multi-center model for research as practiced by NIH. Collaboration across institutions allows the division of work and sharing of resources. Incremental improvements in methods can be contributed by any member and benefit all. Each member can contribute specialized knowledge and perform special roles, e.g. instrument or software development. The cost savings of collaboration increases the amount of money that can be devoted overall to increasing sample size or doing more studies.

- In developing multi-center plans it is important to get the agencies involved from the beginning. Neither researchers nor sponsors can come in with a finished plan. Planning has to be both a top down and bottom up process.

- More research is necessary to describe performance at the extremes. On the one hand, this would help us to know how individuals successfully cope with limitations in function. On the other hand, it would help us identify the limits of design intervention – where environmental supports provide only marginal and ineffective impact.

- Involving clinicians in the collection of data may help to obtain a lot more data because they have access to the research participants. But it is difficult for clinicians to collect data when they have other tasks to do and reliability could be a problem. They would have to be paid and trained.

9. IMPROVING DATA COLLECTION METHODS

There was a general consensus that automated techniques for data collection are necessary to improve effectiveness of anthropometrics research and that three dimensional data collection strategies are necessary to understand functional tasks and build models. Automation reduces the cost of data collection significantly because it reduces the overall time necessary to measure each research participant. It also can improve reliability and accuracy. The most important advantage of automated systems is the ability to measure points in three dimensions, which is very difficult to do manually. There are many competing commercial technologies. They include stereo photography and video, 3-D body scanning, electro-mechanical probes, motion analysis using infra red video, motion analysis using electro-magnetic sensors. Some researchers have developed their own unique devices, like John Kozey and his associates who used a system of cables and strain gauges to measure reaching envelopes. Each methodology has its advantages and disadvantages.

The workshop participants had many recommendations on how to improve data collection techniques:

- Use video based motion analysis as much as possible. Motion analysis is very expensive and not suited for field use but having

a baseline to which other methods can be compared would be a good first step in 3-D anthropometry of people with disabilities.

- Motion capture systems can be utilized to characterize motions used in various functional tasks, full body posture and postural changes. This will avoid overly simplistic representations of motions like reaching. Static measurement approaches do not provide information of this type yet for many design tasks, understanding the way people with disabilities move can be very valuable, especially when it captures different parts of the body moving in synchronicity.

- 3-D anthropometric measurement methods have to be validated. This can be accomplished by comparisons using different equipment, testing with objects having known locations in space and repeatability studies. Many sources of error can affect 3-D anthropometrics, including improper landmark locations, poor calibration of equipment, the influence of environmental conditions (e.g. lighting) and interference by objects in the environment. The accuracy of electro-magnetic sensor arrays, for example, can be affected by metal from wheelchairs depending on the location of probes in relationship to the signal receiver. Moreover, intrusive technology like wires, instrument packs and harnesses, can constrain behavior and alter the performance of a task. Finally, some methods, like laser scanning, may not work with populations of people who have difficulty adapting to the constraints of the technology, e.g. staying still for 15-20 seconds.

- Data fusion applications should be explored. Fusion techniques can be used to combine data collected at multiple sites (macro-analysis) as well as combining several data streams collected simultaneously at one site (micro-analysis).

- Validation of free reach data is needed. Many questions were raised about the usefulness of data on free reach (reach envelopes without associated tasks). Several participants questioned whether such data can be applied reliably to the design of actual task environments. Determining the predictive validity of free reach could demonstrate that such data is not useful for design. On the other hand, relationships between free

reach results and reaching while lifting or doing other tasks could be established that would allow estimates of functional reach envelopes to be derived statistically from free reach data.

- Laboratory data needs to be validated against actual performance of tasks in the real world. The motivations, expectations and meaning of laboratory-based research may not result in the same level of performance as in the real world. There is evidence that people voluntarily exert themselves more in the real world than in a laboratory setting

- Methods for estimating and computing the center of mass are needed, especially for people who use wheelchairs. It is impossible to develop accurate biomechanical models without having that data but it is difficult to obtain with current means.

10. INCREASING COMMUNICATIONS AND DIALOGUE

An important underlying theme of the discussion was continuing and expanding communications and dialogue about the issues addressed at the Workshop. Participants realized that the anthropometrics of disability is important to many stakeholders, not all of whom were well represented at this first gathering. They also recognized that the Workshop was only a beginning to what could become a long-term endeavor fueled by mutual interests. While the Workshop was focused on discussion among experts, those present understood the importance of education and outreach to other interested parties. In particular, they voiced an interest in educating both research sponsors and "consumers," design and rehabilitation professionals, manufacturers, code officials and developers, and end users of products and environments.

Recommendations for increasing communications and dialogue included:

- Work with the Access Board, NIDRR and the Department of Justice to develop research plans. These plans could be based on patterns of complaints and needs for information that surface during the process of resolving complaints.

- Although the Access Board is focused on regulatory activity, other agencies could take the lead in developing best practice as opposed to minimum standards. These could be leadership documents that could point the way toward changes in the regulations over time. For example, performance based standards that utilize computer models, use of outcome measures that focus on comfort or task effectiveness, etc.

- Use existing data, best practice information and expert opinions to augment codes. Such information could be used to develop more exceptions in warranted cases and variations that would be appropriate to certain facility types. This would be a preliminary step before enough data is available to revise codes to reflect the differences in user populations and environmental context.

Future communications and dialogue could focus on specific issues that are of concern to a variety of practitioners and researchers, including engineers, rehabilitation therapists, human factors specialists and designers. Some of these include:

- Developing standardized postures for measurement of people with disabilities

- How data fusion and data mining could be applied to functional anthropometry

- Effective ways to present structural and functional anthropometric data for use by designers

- How-to seminars would be valuable contributions to the field. They would educate people on the issues and provide guidance from more experienced people to those just starting in this field. Such events would also be good dissemination avenues for promoting and disseminating standardized methods and approaches to anthropometry.

- There was a strong consensus on the need to develop a dialogue between researchers and CAD software developers. The focus should be on standardizing measurement, data collection and data reduction methods to aid integration of databases into the

design process.

- There is a need for more dialogue between human factors researchers and the Access Board, Department of Justice and other government agencies charged with developing and enforcing regulations. This dialogue can help agencies to understand the value of human factors research as well as the variety of different methods that can be used to address information gaps.

- More cooperation between the Access Board and NIDDR is needed to develop research priorities and martial funding to address critical issues. Other agencies can be recruited to provide funding related to their specific interests and needs, e.g. housing, transportation, etc.

- A "congress" on terminology under the auspices of an ISO committee would be a very good initial step toward standardization in anthropometry. It is important to develop a good document to start so that developing consensus does not take a very long time.

- A means for developing collaboration between groups doing complementary work would facilitate cost effective use of resources. Complex topics like reach with loads and forces exerted may require specialized facilities and complementary types of research. This would be easier to accomplish with a consortium than individual research groups trying to do it all.

- Setting up a computer discussion list would enable continued communications among the attendees. The list could help everyone communicate information on conferences, new software, new measurement technologies, publications and other valuable information. It could also be used to solicit advice and information on available data on a topic, research methods and policy initiatives.

- Take a global perspective in communications and dialogue to get others involved. It is especially important to involve developing

countries. There are international organizations that could be involved in this effort. For example, the International Center on Technical Aids, ISO and the International Ergonomics Association.

EXECUTIVE SUMMARY

GENERAL OVERVIEW

The Workshop brought together an extraordinary group of people. Their experience and knowledge was diverse and deep. The presence of government officials, software developers and designers as well as researchers ensured that the discussion was kept relevant and focused on solving very real needs for information in the field of accessible and universal design. Excellent presentations and extensive discussion enabled us to have a thorough dialogue on the major issues facing the advancement of the field.

It is clear that two of the "consumers" of anthropometric research, government officials and designers, need more information than the current state of the science provides. Computer technology is creating opportunities to put a high level of anthropometric knowledge into the hands of all stakeholders in the design process. Human modeling programs can access databases of information on people with disabilities just like they do for the general population. Since human modeling software can be integrated with computer aided design (CAD) software, models of buildings or products can be tested with human models of people with disabilities. There will soon come a day when designers, clients, building code officials, consumer advocates and other stakeholders can explore three dimensional models very thoroughly before finalization of the design using a variety of computer based tools. This exploration could involve testing grip sizes, seating dimensions, clearances and even the force of operation against data on the body sizes, reach ranges and strength of different groups in the population of people with disabilities. Sophisticated human modeling software is already used this way in safety analysis, aircraft and automobile design and other applications for people without disabilities. At present, this software is quite expensive but lower cost versions are beginning to enter the market.

Human models can be used to represent people of different sizes, simulate how people move and, if they include biomechanics modules, compute the forces on the human body in different postures and different loading conditions. At the University of Michigan's Center for Ergonomics, the RERC on Wheeled Mobility at the University of Pittsburgh and Loughborough University in the UK, among other places, researchers are developing such human models of people with disabilities. While they will initially be used by specialists and well endowed design operations, less complicated programs like the one described and demonstrated by Joachim Eriksson from Lund University illustrate how computing can make it easy and affordable for rehabilitation professionals and other non designers to use anthropometric data. The open source code approach used by Eriksson could benefit the widespread utilization and adoption of such software.

Currently we do not yet have access to accurate and reliable human models of people with disabilities that can easily be used in design. In particular, we do not have three-dimensional databases which allow the development of true virtual human manikins with disabilities and we do not have enough data on functional anthropometry. While there have been many studies completed, Bradtmiller and Kozey and Das have demonstrated that the results of these studies are not consistent. To generate the kinds of data needed for human models is not a simple task. Interpolating data collected from the able-bodied population is not advisable because there is enough information to indicate that the anthropometry of people with disabilities is different, especially those who use wheeled mobility devices.

These knowledge gaps define the agenda for the anthropometry of disability in the next 10-20 years:

- developing 3-D databases,
- understanding the functional anthropometry of disability,
- collecting reliable and valid data, and
- organizing data into comprehensive and accessible databases.

In addition, there were several emerging research approaches that could provide additional sources of information on human performance issues of relevance to accessible and universal design.

DEVELOPING 3-D DATABASES

Three-dimensional anthropometric data can be collected in many ways. Mollenbroek described several methods currently in use. The techniques available include traditional manual measurement with anthropometric tools, full body scanning, photo-stereogrammetry, video motion analysis, motion analysis using electromagnetic sensor arrays and 3-D digitizing of landmarks. With photographic, video and scanning methods, wheelchairs will obscure landmarks on the body. Data from electromechanical sensor arrays are susceptible to distortion around metal. It is very difficult to collect 3-D data using manual methods without the use of jigs or other apparatus.

Today, automated data collection is preferred in most cases due to the lower cost for data entry and analysis. However, almost all the tools above require a dedicated controlled setting to collect accurate data and the equipment is hard to move from place to place. This limits access to large numbers of participants and increases the cost of data collection because people with severe disabilities have limitations in mobility and need accessible transportation.

Paquet and his associates described a portable method for automated data collection of 3-D coordinates that compares favorably in accuracy and reliability to manual methods. Das and Kozey described an apparatus that can be used to collect range of reach data with lower cost than motion analysis systems. Thus there are alternatives to costly laboratory based equipment. As technology improves, the availability of more advanced portable tools may solve some of the major logistical and economic problems in anthropometry.

Ideally, anthropometric, kinematic and biomechanical data should be collected simultaneously. Chaffin and his associates reported on a current study using such an integrated data collection strategy. However, this

approach is very time consuming and expensive, particularly when biomechanics data is included. It can only be used economically with relatively small samples at one time, not samples with 1000 or more people, which is highly desirable in this type of research.

Two complementary strategies can be used to assemble the databases needed. The first is to conduct large-scale surveys that aim for inclusive samples and high "confidence levels." Such surveys can collect comprehensive structural and limited functional data at reasonable costs. The second is the use of small samples with high levels of instrumentation to understand the relationship of anthropometric, kinematic and biomechanic factors. Although 3-D motion analysis is the "gold standard," it may not be necessary to collect such kinematic data in large surveys. Studying how people move and developing biomechanical models can be done with smaller samples (e.g., those with the most severe impairments) in order to provide designers with rich information about the environmental or task characteristics that are the most problematic for the sample.

UNDERSTANDING THE FUNCTIONAL ANTHROPOMETRY OF DISABILITY

Structural anthropometric data on disability is very important. It provides information on the minimum sizes and clearances required for products and small scale environments, for example, the size of the space needed to accommodate a wheelchair and its passenger or the eye height of a seated individual. Nowak demonstrated how structural data from body links can be used to mathematically compute reach envelopes. One could also use structural data to compute the clearances necessary to accommodate a moving person. However, such computations currently cannot really be used to determine functional reach unless it is defined solely as maximum reach potential. Structural measurements alone do not reflect limitations in joint rotation or the influence of flaccidity, incoordination and fatigue on reaching ability nor do they reflect variations in gait or abilities to propel and maneuver a wheelchair. For these reasons, correlations between muscle strength and structural anthropometric measurements are very low.

Functional anthropometry expands on structural data to provide information on the actual reach trajectories and envelopes and clearances needed to move through a space and manipulate parts of the environment. It also includes examining the relationship between the application of force and movement. So, for example, researchers at the RERC on Wheeled Mobility and the Center for Ergonomics are studying the dynamics of propelling manual wheelchairs and repetitive reaching tasks. This involves modeling the shoulder and the pelvis under stress. Such models will provide an understanding of how to reduce injuries and accidents for wheelchair users.

An important area of functional anthropometry that has been neglected is the development and use of outcome measures. Two types of outcome measures can be devised, observational measures and psychophysical measures. The former include indicators of satisfactory performance like hitting a target or placing an item on shelf or observer evaluations, e.g. level of assistance needed. The latter are subjective rating scales that provide an indicator of what the participant thinks about the task being performed, e.g. level of comfort or acceptance. Outcome measures requiring observer judgement or subjective opinion are subject to bias and error due to intra rater variation (same person rates the same thing differently at different times), inter rater differences (different people rate the same thing differently) or lack of sensitivity (scale doesn't pick up real differences). Rigorous development and testing are necessary to insure that outcome measures are effective.

COLLECTING RELIABLE AND VALID DATA

Some argue that functional concerns can be examined with computer animations of people in movement. Animations, unlike anthropometric models, are not tied to databases of measurements or computational models of movement and biomechanics. Rather, the motions and sizes of the figures are based on some rough assumptions about the size of people and assistive devices and the way people move. Computer animation is very convincing and useful for illustrative purposes but the external validity and generalizability to large populations is questionable. If an image looks good on a computer screen, it will often be accepted as fact even though it is not an accurate representation of

how real people move and function. A true human figure model is parametric. Body sizes can be scaled to represent data collected from real people. It also uses computational techniques to produce movement based on kinematic and biomechanic abilities.

The validity of models is therefore based on the data that forms the basis for scaling the figures and computing motion and/or biomechanic loading. Two major issues affect the reliability and validity of data collected through anthropometric research: sampling methods and data collection methods.

Sampling Method

Sampling is the key to producing databases that are representative of the population. The consensus of the experts at the Workshop was that larger samples are desirable to improve the generalizability of data on people with disabilities. But, recognizing that recruiting and assembling large samples of people with disabilities is very difficult and expensive, especially in one place, all agreed that smaller samples can be used if it is possible, over time, to combine data together to eventually produce a larger, more comprehensive database. Bradtmiller described the variables associated with establishing sample size with a specific focus on confidence level (% of population represented). He argued that for populations of people with disabilities, reduced confidence levels may not be a serious problem. He also demonstrated that proportionate sampling strategies, the conventional approach to stratification, may not be the best for this population. Although type or cause of disability is the conventional approach to stratify a sample of people with disabilities, Bradtmiller demonstrated that this approach results in some serious limitations and may actually compromise generalizability. Lenker and his associates proposed two alternative approaches, method of mobility and level of functional independence. These methods may reduce the cost of recruitment and sample size needed to achieve acceptable confidence levels.

Data Collection Methods

The accuracy of measurements is determined by how precise the measurements can be taken and the degree of error or distortion introduced by the measurement method. Roebuck, as well as Paquet and his associates, described many sources of inaccuracy. They include stability and sensitivity of the measurement device, selection and definition of landmarks, missing or distorted body parts, inability to reach landmarks, inability to hold standard postures, lack of proper training in taking measurements, excessive movement on the part of the person being measured and ethical concerns regarding removal of clothing or use of skin tight clothing.

There are solutions to these problems. Alternative landmarks can be selected when others are not accessible or missing. Normal resting postures can be used as opposed to standard anthropometric postures. Methods of estimating dimensions can be devised when a full set of landmarks is not available. Landmarks can be marked on top of clothing with washable markers. Good training is very important for maintaining accuracy across data collectors. As Paquet et al. demonstrated, completing careful reliability and validity studies prior to the collection of data can document accuracy of methods and identify the need to revise them. People with disabilities are valuable consultants for insuring that research tasks will not be misinterpreted, embarrassing or invade the privacy of the participants.

Based on experience in developing methodology for the anthropometry of disability, work is underway at the RERC on Universal Design at Buffalo, in collaboration with John Roebuck, to produce an illustrated manual on landmark definition that will include recommendations for responding to the issues above.

ORGANIZING DATA

Developing consensus on a standardized methodology and training approach could go a long way toward creating the consistency required for merging small databases into a larger comprehensive database. Hobson described efforts by an ISO Committee to standardize terminology, definition and measurement of wheelchair seated posture. This work could be expanded to include attention to the full spectrum of issues in the anthropometrics of disability. Since there are many automated data collection tools, standardization should focus on landmark definitions and standard procedures for checking reliability and validity. It could also incorporate best practices for different data collection tools, for example, approaches to avoid distortion with multisensor electromechanical arrays. Another area for standardization should include the form and content of databases for use in human modeling systems. This would facilitate the rapid integration of the databases into analytical and design tools.

Once data has been collected and analyzed, it is critical that it can be organized and presented in a manner that will be useful for all stakeholders. Here is where human modeling has great utility because models can be used to generate many different kinds of data and to visualize it with a high degree of flexibility and accuracy. For example, a model of a wheelchair user could allow the user to substitute different wheelchairs and fit them to people with a wide range of different statures. Different views can be taken of the same model to get different perspectives, and, models can be manipulated into different postures. Using any model as the basis, many useful analysis tools can be created to help designers test their work while it is still in the design stage. For example, a model could be adapted as a tool to explore variations in sight lines for seating. This would allow architects to understand the implications of their designs on visibility. More conventional tools like templates or charts can be generated directly from the model as well.

Most anthropometric surveys focus on the person and thus provide generalized databases, but it is difficult for the average designer or standards developer to interpret such data. Specific information is often needed by both groups of “knowledge consumers.” Porter and Steinfeld both emphasized the importance of collecting data on specific tasks.

Good precedents for this approach are the automobile industry and the defense industry in which very specific studies are completed on anthropometrics related to seating and instrument panels. Reed proposed that, using such data, human figure models should be augmented with task specific models that can be used to test various conditions accurately. Although the development of general human figure models of people with disabilities is a useful goal, the addition of task-specific models would provide more accurate and detailed set of analytic tools. Ideally, the task-specific models should be integrated with the figure model with a good interface.

Porter suggested that, in the absence of comprehensive models tied to large databases, individual models of a range of people with disabilities could also be very useful. Designers could call up a set of diverse "virtual users" to test out a design, or, at least, to understand how a range of people might use a place or product. Steinfeld demonstrated how abilities can be mapped onto a representation of a space or product, reducing the interpretation required for applying anthropometric data to design. Models that allowed such representations of data could make it much easier for designers and other users to understand the implications of anthropometric differences and limitations in ability.

EMERGING RESEARCH APPROACHES

Three emerging research approaches were presented and discussed at the Workshop: survey research, ethnographic studies and multi-source data fusion. Sanford illustrated how survey research can be an effective method to identify unmet needs and to evaluate the effectiveness of standards and guidelines based on anthropometric data. As such, it can be used to provide feed-back and feed-forward loops to a research program. Hewner argued that ethnographic research is a very useful method for identifying and defining outcome measures. She demonstrated how qualitative data can be used to construct scales. Such an approach is well suited to a user centered research perspective. Llinas described the concept of data fusion, which is a mathematical approach to combining several sources of information to make conclusions. Data fusion can be very valuable in uncovering important

findings by analyzing sets of data generated by independent studies. It can also be helpful in making sense of several different streams of data from different sources, e.g. several different kinds of automated sensors.

ACTION AGENDA FOR RESEARCH

It would be easy to provide a very long list of action items based on the recommendation made at the Workshop. The full set of recommendations is available in the body of the report for reference purposes. Here, we will focus on specific readily achievable actions that could advance the field in the near future. The action agenda is organized using the following goals:

- Standardize methods for collecting data,
- Improve data collection methods to provide better quality data and increased cost effectiveness
- Develop modeling methods that capitalize on current and future information technologies,
- Organize anthropometric databases in more useful ways
- Develop mechanisms for further communications and dialogue among all the stakeholders.

Taking each of these goals in turn, some concrete action items are proposed below:

- Standardize methods and databases as much as possible
- Develop a manual of landmark descriptions (underway by RERC on Universal Design at Buffalo)
- Adopt or develop reliable outcome measures for use in functional anthropometry

- Start an ISO effort to develop consensus protocols for data collection that address the specific challenges posed by samples of people with disabilities

- Publicize these efforts in the human factors community and among computer model developers (underway by RERCs)

- Develop a consensus database structure for research databases

- Collaborate on the database structure with human figure modelers

- Develop an archive of research databases with standards of quality for contributions

- Improve sampling and data collection methods

- Put more emphasis on collecting functional data and data for task specific applications

- Encourage researchers who study general populations to include people with disabilities in their samples

- Develop more effective stratification methods

- Develop innovative methods for collecting 3-D data that are more portable and less costly than the high quality but expensive laboratory approaches

- Test new data collection methodologies through cross validation with established methods

- Utilize intra-rater and inter-rater reliability studies in all research

- Validate data collected in the laboratory against data on function collected in the real world

- Utilize more sophisticated outcome measures when studying functional tasks

- Develop modeling methods that capitalize on available software tools
- Encourage software developers to include databases of people with disabilities
- Develop collaborations between researchers and software developers
- Develop full-feature and low-level modeling systems
- Test the predictive ability of models with real world examples
- Integrate models with computer aided design systems
- Utilize an "open source code" modeling system as an inexpensive way to implement models from databases (available through Eriksson)
- Organize data in more useful ways
- Develop both human figure models and task specific models
- Illustrate how abilities map onto the environment rather than simply reporting the abilities of the target population
- In the absence of comprehensive databases, develop models of individual people with a range of abilities
- Explore data fusion as a technique for analyzing multiple sources of data
- Re-analyze existing data bases in light of contemporary needs
- Develop computer interfaces to databases (Molenbroek and his associates have developed such a tool)

- Display data and case studies on the web (RERC on Ergonomics has developed an example of such a system for workplace adaptations)

- Develop mechanisms for further communications and dialogue

- Publish versions of Workshop papers in journals

- Establish an internet discussion list for communications among stakeholders

- Obtain funding to start a web site on anthropometrics of disability (could start with publishing this report)

- Find funding to hold follow-up workshops at conferences or additional stand-alone events

- Develop consortia or partnerships between research institutions to share research methods

- Develop multi-site proposals to benefit from synergy and improve utilization of special resources

IMPLICATIONS FOR THE ACCESS BOARD & NIDRR

The Access Board needs data and tools to help them generate improved guidelines and requirements for accessible design. Clearly the Board would benefit from a systematic program to develop accurate and comprehensive databases on the anthropometry of people with disabilities. In addition, the development of valid and accurate computer models would provide powerful tools they could use to identify needs for new guidelines and requirements and also to evaluate the value of proposals to change existing guidelines and requirements.

In her presentation, Lois Thiebault expressed the Board's frustration with the existing resources available in this field and raised a challenge to find alternatives. The Workshop concurred with the Board's assessment

that the available data on anthropometry of disability needs much improvement. As for alternatives, the main recommendation coming out of the Workshop is to develop computer based figure models of people with disabilities. A comprehensive model is a long way off because developing the underlying database will take many years. However, even with a small amount of data, basic human figure models of a limited number of disabled individuals can be generated fairly rapidly using actual measurements. These preliminary figure models can be used to test the value of modeling and to gain experience for developing a scalable model tied to an underlying database of comprehensive data. Ericksson's open source program could be adopted as a starting point and/or collaborative project could be undertaken with commercial software manufacturers.

One of the other important recommendations to come out of the Workshop was a call for more communication and dialogue between the research community and government agencies entrusted with implementing accessibility laws. Besides the circulation of this report, an important first step might be for the Board and NIDRR to organize a briefing for the Board members and staff on the results of this Workshop. It would also be useful for the Board and NIDRR to support an effort to educate the various stakeholders, including both government and industry, about the nature and value of anthropometrics and human factors research on disability. Experts in the human factors research community acknowledge that it is difficult to convince stakeholders of the value of such research. Yet, there are many success stories, not the least is the research that led to the current technical provisions in the ADAAG. In the mid '70's the U.S. Department of Housing and Urban Development, the Easter Seals Society and the President's Committee on Employment of People with Disabilities, joined forces to sponsor a major study (The New ANSI Standards Study) on the human factors of accessibility that was directed by Edward Steinfeld. That study developed the database that was used as the basis of most accessibility codes in the U.S. Regardless of the gaps in that effort that are evident today, it advanced the field significantly from the previous state of the science and most of the findings have withstood the test of time. A similar effort could help move the field ahead once more.

The research community can provide technical assistance to the Board in maximizing the usefulness of the existing knowledge base. Although

members of the Board and staff may not perceive the value of data in existing reports and publications, researchers often have insights and knowledge that can be very helpful in gaining greater utility from what we already know. For example, at the workshop, Lois Thibault posed a question in her paper related to call boxes that appears unanswerable from current research. Yet, there is data in a report of previous research that could be applied directly to the question at hand. But, to understand how may require some help from specialists. Or, as another example, there has been a great deal of research in the field of human-computer interaction that is useful and applicable to the Board's new mandate in information technology.

Follow up activities in the area of communications and dialogue could include, as recommended at the Workshop, reviews of ADA complaints lodged with the Justice Department, information requests to Justice and the Board and public hearings held during the revision of ADAAG to identify priorities for research. It may be discovered that many of the information needs identified can already be addressed based on existing knowledge and basic human factors principles.

In fact, there is much useful information in databases previously developed that could be reanalyzed in response to new questions. The Board and NIDRR could fund small studies that mine this information and improve on its utility by organizing and presenting it more effectively, in particular, developing working computer based figure models and task specific models. For example, the IDEA Center, home of the RERC on Universal Design at Buffalo, has several databases in its possession that are ripe for such treatment: the aforementioned New ANSI Standards study, the Hand Anthropometric Study (sponsored by the Access Board), which collected anthropometric and biomechanic data on over 100 people with hand and arm disabilities during the mid '80's, and a series of full scale modeling studies on storage and bathroom design. Surely there are other databases assembled by researchers around the world that have useful information.

Since much of the research on which codes were based was completed, there has been a significant improvement in anthropometric research methods as well as much better approaches to organizing information for use by designers and other stakeholders. Currently, the RERC on

Universal Design at Buffalo is engaged in a long-range study to develop a prototype anthropometric data base of the 3-D body size, reaching capabilities, strength and maneuvering abilities of those who use wheelchairs. The first phase is developing and testing methodologies, collecting data on a sample of wheelchair users and developing new ways to organize and presenting the data. We plan to work with software developers to implement modeling software that can be used for developing codes and standards and also for design purposes. And, once the methods are tested and documented, we hope to disseminate the methodology by recruiting additional data collection sites. The Workshop was very timely in that the RERC can adopt many of the recommendations in this report to make its work as effective as possible. Other RERCs are also engaged in anthropometric research activities. Further communication between the Board and the RERC's including briefings on our findings and discussion of methods would be very valuable.

Perhaps one of the most important implications of the Workshop is the obvious need for generating more funds for research in this field. The Access Board and NIDRR have recently been the only agencies funding research on accessibility. They could take the lead in developing a plan for research support that would involve other agencies in this effort. The Departments of Housing and Urban Development, Transportation, Interior, Defense, State, Health and Human Services, and Justice as well as the General Services Administration all have stakes in improving the knowledge base in anthropometrics and disability. With contributions from these agencies and the National Science Foundation, a lot more could be accomplished in a lot less time. Coordination with initiatives in the European Union, Japan and Australia would be very valuable too. The private sphere has not played a role in funding human factors research on accessibility although they do fund human factors work in other fields. There are successful models of public and private cooperation in human factors research. In fact, a large-scale anthropometric study such as the CAESAR Project, organized by the Air Force and involving many private organizations, could be a good vehicle to expand activities in the anthropometry of disability.

APPENDIX 1: PARTICIPANTS

ACCESS WORKSHOP CONTRIBUTING AUTHORS

Bruce Bradtmiller
Anthrotech
503 Xenia Avenue
Yellow Springs, OH 45387
(937) 767-7226
bruce@anthrotech.net

Donald Chaffin
Center for Ergonomics
University of Michigan
1205 Beal Avenue
Ann Arbor, MI 48109
(734) 763-2245
dchaffin@umich.edu

Juliette Cooper
Universal Design Institute
University of Manitoba
201 Russell Building
Winnipeg, MB R3T 2N2
Canada
(204) 789 3371
jcooper@ms.umanitoba.ca

Rory Cooper
Human Engineering Research
Laboratories
University of Pittsburgh
5038 Forbes Tower
Pittsburgh, PA 15260
(412) 383-6590
rcooper@pitt.edu

Biman Das
Industrial Engineering
Dalhousie University
6230 South Street
Halifax, NS B3H 3J5
Canada
(902) 494-3296
Biman.Das@Dal.Ca

Clark Dickerson
Center for Ergonomics
University of Michigan
1205 Beal Avenue
Ann Arbor, MI 48109
(734) 936-0146
cdickers@umich.edu

Joakim Eriksson
Division of Ergonomics & Aerosol Technology
Dept of Design Sciences
Lund University
Box 118 SE 22100
Lund, Sweden
+46 46 222 8015
joakim.eriksson@design.lth.se

David Feathers
RERC on Universal Design at Buffalo
University at Buffalo
State University of New York
342 Bell Hall
Amherst, NY 14260
(716) 645-2357 x 2113
feathers@eng.buffalo.edu

Sharon Hewner
Applied Anthropological Res.
Department of Anthropology
University at Buffalo, State University of New York
4117 Old Ransomville Road
Ransomville, NY 14131
(716) 791-4384
hewner@buffalo.edu

Douglas Hobson
SHRS-RST
University of Pittsburgh
5044 Forbes Tower Room
Pittsburgh, PA 15260
(412) 383-6586
dhobson@pitt.edu

Alicia Koontz
Human Eng. Research Lab
VA Pittsburgh HealthCare System
7180 Highland Drive
151 R-1
Pittsburgh, PA 15206
(412) 365-4833
amkst63@pitt.edu

John Kozey
School Of Health and Human Performance
Dalhousie University
6230 South St.
Halifax, NS B3H 3J5
Canada
(902) 494-1148
jkozey@is.dal.ca

James Lenker
RERC on Universal Design at Buffalo
University at Buffalo
State University of New York
515 Kimball Towers
Buffalo, NY 14214
(716) 645-3141 x 109
lenker@acsu.buffalo.edu

James Llinas
Center for Multisource Information Fusion
Industrial Engineering Department
University at Buffalo
State University of New York
315 Bell Hall
Amherst, NY 14260
(716) 645-2357 ext. 2105

Bernard Martin
Industrial & Operations & Engineering
University of Michigan
G650 IOE Building
2117
Ann Arbor, MI 48109
(734) 763 0189
martinbj@umich.edu

Johan Molenbroek
Faculty of Industrial Design Engineering
Delft University of Technology
Jaffalaan 9, 2628 BX
Delft, The Netherlands
+31 15 278 3086
j.f.m.molenbrook@io.tudelft.nl

Ewa Nowak
Institute of Industrial Design Science
Warsaw 00-236
5/7 Swietojerska STR
Poland
48 22 831-0903
ergonomia@iwp.com.pl

Victor Paquet
RERC on Universal Design at Buffalo
University at Buffalo
State University of New York
342 Bell Hall
Amherst, NY 14260
(716) 645-2357 x 2113
vpaquet@eng.buffalo.edu

J. Mark Porter
Dept. of Design & Technology
Loughborough University
Leicestershire LE11 3TU
United Kingdom
+44 1509 223026
j.m.porter@lboro.ac.uk

David Rapson
Universal Design Institute
University of Manitoba
201 Russell Building
Winnipeg, MB R3T 2N2
Canada
(204) 474-6450
rapsond@cc.umanitoba.ca

Matthew Reed
UMTRI
University of Michigan
428 UMTRI
2150
Ann Arbor, MI 48109
(734) 936-1111
mreed@.umich.edu

Laurie Ringaert
Universal Design Institute
Faculty of Architecture
University of Manitoba
201 Russell Building.
Winnipeg, MB R3T 2N2
Canada
204-775-1222
ringaer@mts.net

John Roebuck, Jr.
Roebuck Research & Consulting
P.O. Box 3338
San Monica, CA 90408
(310) 394-0807
johnroebuck@earthlink.net

Jon Sanford
VA Rehab R & D Center
1670 Clairmont Road (151R)
Decatur, GA 30033
(404) 321-6111 x6788
jasanf@aol.com

Edward Shwedyk
Universal Design Institute
Faculty of Architecture
University of Manitoba
Winnipeg, MB R3T 2N2
Canada
(204) 474-9651
shwedyk@cc.umanitoba.ca

Edward Steinfeld
RERC on Universal Design at Buffalo
University at Buffalo
State University of New York
3435 Main Street 378 Hayes Hall
Buffalo, NY 14214
(716) 829-3485 x 327
arced@ap.buffalo.edu

Lois Thibault
US Access Board
1331 F Street NW #1000
Washington, DC 20004
(202) 272-5434 x132
thibault@ACCESS-BOARD.gov

Linda van Roosmalen
RST Injury Risk Assessment & Prevention Lab
University of Pittsburgh
5044 Forbes Tower
Pittsburgh, PA 15260
(412) 656-3687
lvanroos@pitt.edu

Gerald Weisman
Rehab Engineering Technology
Vermont Technical College
35 Western Avenue
Randolph Center, VT 05061
(802) 863-3222
jweisman@vtc.vsc.edu

Nancy Womack
Center for Ergonomics
University of Michigan
172 IOE Building
2117
Ann Arbor, MI 48109
(734) 936-1111
nwomack@umich.edu

Charles Woolley
Center For Ergonomics
Industrial & Operations &
Engineering
University of Michigan
Room G624, IOE Building
1205 Beal Avenue, North Campus
Ann Arbor, MI 48109-2117
(734) 763-0570
cwoolley@umich.edu

OTHER ATTENDEES

James Bostrom
Disability Rights Section
U.S. Department of Justice
P.O. Box 66738
Washington, DC 20035
(202) 307-2584
jim.bostrom@usdoj.gov

Julie Cameron
Access Australia Consultants Pry.
Ltd
20 Clifford Street
Mosman NSW 2088
Australia
+61 2 9960 4222
access@ozemail.com.au

Sarah Endicott
CATEA
Georgia Institute of Technology
490 Tenth Street
Atlanta, GA 30332
(404) 894-1411
sarah.endicott@arch.gatech.edu

Molly Follette-Story
Center on Universal Design
North Carolina State University
16438 East Dorado Avenue
Centennial, CO 80015
(303) 699-8133
molly_story@ncsu.edu

John J. Miller
Dept. of Architecture
Mississippi State University
P.O. Box AQ
Mississippi State, MS 39762
(662) 325-2202
jmiller@sarc.msstate.edu

William Peterson
NIDRR
U.S. Department of Education

330 C Street SW
Washington, DC 20202
(202) 205-9192
william_peterson@ed.gov

David Pinchefsky
President.
NexGen Ergonomics Inc
3400 de Maisonneuve Boulevard West
Suite 1430
Montreal, PC
Canada
(514) 685-8593
pinchefsky@nexgenergo.com

Tara Reilly
School of Health & Human Performance
Dalhousie University
6230 South Street
Halifax, NS
Canada
(902) 494-1148

Robert Topping
Sheridan College
7899 Mc Laughline Road Box 7500
Brampton ON L6V 1G6
Canada
(905) 459-7533 x5051
bob.topping@sheridanc.on.ca

APPENDIX 2: SUMMARIES OF THE PAPERS

The short summaries below describe the objectives, content and conclusions of papers presented at the Workshop. The full papers are included in a separate volume.

1. DISABILITY ANTHROPOMETRICS: A RESEARCH USER'S DILEMMA

LOIS E. L. THIBAULT

The U.S. Access Board is the agency that develops and authors the Americans with Disabilities Act Accessibility Guidelines. The Guidelines are the primary design documents used for implementation of the Act (ADA). The Board has long relied on the findings of anthropometric studies in developing the technical standards in the Guidelines that are used to design accessible environments. Paragraph 2.1 of the ADA Accessibility Guidelines (ADAAG) reads: "The specifications in these guidelines are based upon adult dimensions and anthropometrics..."

New consumers seeking accommodation, the conflicting needs of a broad range of users with little anthropometric commonality, and the lack of a usable database on the characteristics of people with disabilities have made it difficult to apply existing anthropometric research to new conditions. Sampling, management, and ethical concerns connected with anthropometric research compromise the reliability of data collection. The frontier has shifted from physical accessibility to communications, data, and IT accessibility. Progress towards implementation of universal design in the built environment has raised the bar, particularly for those who have age-related disabilities, but environmental barriers continue to exclude.

As it enters a new research and rulemaking decade, the Board finds itself questioning the usefulness of human factors studies in determining

parameters for building and facility design and is actively seeking approaches that may be more appropriate for a technological age.

2. COMPUTER MODELING AND ANTHROPOMETRY: ADVANCES FOR WHEELCHAIR USERS

JOHN A. ROEBUCK, JR.

Computer human modeling is a rapidly advancing technology that offers significant potential benefits for analysis of accommodations for people with disabilities in general, and specifically wheelchair users. However, realization of such benefits requires adaptations and new developments that incorporate the special attributes of users with disabilities, particularly in regard to engineering anthropometry. Anthropometry is concurrently undergoing advances resulting from the diverse needs of computer human modeling and the information needs of professionals designing accommodations for people with disabilities.

This paper describes several of these developments and how they interact to advance the technology of design and evaluation of buildings, wheelchairs, and work site equipment. Included are: new terminology standards and improved formats for descriptions of landmarks and measurements, methods to assist international dissemination, new ways of handling constraints of wheelchair posture when making measurements, new statistical checking approaches during surveys, advances in methods for derivation and estimation of non-measured dimensions, and new methods and terminology for measuring clothed subjects.

3. BEYOND 'JACK AND JILL': DESIGNING FOR INDIVIDUALS WITHIN POPULATIONS

J. MARK PORTER

This paper examines some of the limitations of current anthropometric and biomechanics databases with particular respect to the development and use of 3D human modeling CAD systems. Attempting to design for people who are older or have disabilities demonstrates these limitations most clearly.

The limitations discussed in this paper focus on three main issues:

- The need to apply models to accommodations in which many issues need to be addressed simultaneously.

- The need to provide designers with data that are relevant to the individual, the task and the environment.

- The need to provide designers with appropriate data presented in a highly visual form that can be used efficiently in combination with existing design tools and practices.

Ergonomics experts can be so focused on the issues relating to the end user of a product or service that they may overlook another very important user of their information – namely the designer. Many design companies and manufacturers do not have qualified and experienced in-house ergonomics experts or human factors specialists. Many companies appoint internal personnel to such a role and, consequently, the ergonomics issues are often dealt with by a non-specialist without the formal support that may be required in terms of education, facilities and research networks. For ergonomics experts to truly support widespread design practice, we need to develop and communicate information and methods that meet the needs of designers themselves. The paper concludes with an outline of a design tool that would allow designers to call up computer models of individuals in order to 'test" their designs in development.

4. TOWARDS A STANDARD FOR THE DEFINITION AND MEASUREMENT OF WHEELCHAIR SEATED POSTURE

DOUGLAS HOBSON

Wheelchair seating is a sub-specialty of rehabilitation services that has developed steadily over the past several decades. This practice involves the selection and provision of wheelchair seating products that provide improved body support, movement control, and injury prevention for the wheelchair user. Inherent in this selection process is the measurement and communication of both the anthropometric and postural dimensions of the seated person, as well as the dimensions and location of the person's postural support system components.

There is tremendous variation in the terminology and definitions related to clinical measures of a wheelchair-seated individual. Standard definitions and terms are lacking for measuring and communicating critical postural information in a way that is uniformly useful to service providers, researchers, manufacturers, wheelchair users and payers when selecting and providing wheelchair seating devices. This paper describes the effort to develop standards in order to clarify geometric terms and definitions for specifying a person's anthropometric measures and seated posture as well as terms for describing the spatial orientation of a person's supporting surfaces (seat).

5. DETERMINING ARM-REACH ZONES — REVIEW OF METHODS AND ASSESSMENT OF THEIR USABILITY FOR THE NEEDS OF SHAPING THE LIFE AND WORK ENVIRONMENT OF PEOPLE WITH DISABILITIES

EWA NOWAK

The aim of this paper is to review developments in anthropometrics of reach envelopes and to evaluate them in terms of their usefulness for understanding the needs of people with disabilities. These research methods can be divided into two groups:

- Measurement of the reach envelope in using a three-dimensional reference system An advantage of this approach is that it can describe natural movement of arms very precisely. A disadvantage of this method is that data collection is time consuming.

- Determining reach envelopes mathematically using measurements of body links. This approach is based on calculating the reach envelope using a few somatic characteristics. It is much simpler and easier to use but does not give a precise determination of hand motion trajectory.

The challenge for anthropologists, engineers and designers is to develop a method that is easier to use with people who have disabilities and also precisely estimates reach envelopes.

6. STRENGTH CHARACTERISTICS OF PEOPLE WITH DISABILITIES

GERALD WEISMAN

Almost everything we do requires a certain amount of strength. Accessibility standards such as the UFAS and the ADAAG give limited mention to the need to apply forces while accomplishing everyday tasks. Specifically, Section 4.27.4 specifies the forces "to activate controls shall be no greater than 5 pounds." There is a need for a better understanding of the strength capabilities of people with disabilities in order to guide the development of better accessibility standards as well as design guidelines. Strength capabilities of able-bodied individuals have been researched to better understand how to design work environments to prevent such injuries as low back pain and other cumulative trauma disorders. Understanding the strength characteristics of people with disabilities will improve the design of devices and the built environment. For example, the position of grab bars directly affects the ability of a person to generate the strength necessary to transfer. Integrating anthropometric and biomechanic databases would seem to be an important aspect of future research.

7. METHODS FOR COLLECTING ANTHROPOMETRIC DATA BEARING IN MIND A TOOL FOR PRODUCT DESIGNERS

J.F.M. MOLENBROEK & A.I.M VOORBIJ

To insure a good fit of products for people with limitations, product designers should have a tool at their disposal that helps them to test their design against the sizes and abilities of users with disabilities. However, the current information available is not presented in a way that is useful to designers. Furthermore these data do not adequately reflect the characteristics of most people with disabilities, who tend to be more variable then able bodied users. We studied four existing measuring methods and evaluated them for collecting data using a set of landmarks suggested by Hobson (2001). We concluded that all methods have their drawbacks but photogrammetry is best for collecting data quickly and effectively. Photogrammetry also makes it possible to produce an adequate designer-oriented tool.

8. THREE-DIMENSIONAL MEASUREMENTS, SEMI-STANDARDIZED POSTURES AND CLOTHING: STRUCTURAL ANTHROPOMETRIC METHODS FOR THOSE WITH DISABILITIES

VICTOR PAQUET, DAVID FEATHERS, & JAMES LENKER

Three-dimensional measurement methods allow the locations of many body and environmental landmarks to be considered simultaneously. This provides an opportunity to develop new anthropometric variables and improved computerized human models. With these opportunities come a series of challenges that include a need for newly defined reference points and dimensions and new approaches to minimize measurement error. This paper describes a protocol in which an electromechanical probe is used to measure body points in three dimensions. The new measurement method allows research participants to assume semi-standardized postures and wear light clothing. This approach can be used when measuring those who are unable to maintain the erect postures traditionally required, and provides structural anthropometric data that more closely resemble peoples' natural body sizes and postures. Among the challenges we now face is the development of new analysis tools to help ensure that the data are used appropriately for the improved design of built environments and in human modeling.

9. REACHING AND OBJECT MOVEMENT CAPABILITY IN THE SPINAL CORD INJURED POPULATION

DON B. CHAFFIN, CHARLES WOOLLEY, BERNARD MARTIN, NANCY WOMACK, & CLARK DICKERSON

Human reaching and object movement capability while seated is dependent on maximum muscle strengths in the torso, shoulder and upper extremity as well as balance. This paper presents an attempt to empirically describe and model this phenomenon using biomechanics. The empirical work was conducted using the new University of Michigan Human Motion Simulation Laboratory, which has a facility for robust and accurate three-dimensional measurement of human motions during prescribed tasks. The data gathered are reduced using a kinematics representation of the human body. This model produces the dynamic posture data necessary to define the strength and balance requirements of a task. These data, along with muscle EMGs are being used to understand the different levels of performance and exertion required when people with thoracic level spinal cord injuries perform seated reaching motions.

We also are using a modification of our existing human strength prediction model (3DSSPP). This allows us to compare the data from people with disabilities to normal population strength and seated balance requirements during seated reaching and light load movement tasks. Initial data has revealed some preliminary understanding of the biomechanical nature of the limitations in such task performances. In particular we are documenting the importance of lower torso and hip extensor control to maintain postural balance during those activities that require two-handed reaching and object moving tasks.

10. BUILDING AN ANTHROPOMETRIC DATABASE FOR WHEELCHAIR USERS: A SAMPLING DILEMMA

BRUCE BRADTMILLER

Engineering anthropometry is the application of anthropometric data to problems of design. How we define the population in turn defines the resulting anthropometry. For the general ambulatory population, we know what critical demographic parameters influence anthropometry. In the case of wheelchair users, the critical sampling parameters are not clear. Once sampling parameters are identified, their use in the sample structure is also not clear. Is it important to have data separately on each group that might use a wheelchair or are other approaches more effective or necessary as well? The answer to this question determines how data collection should be structured, but will also determine the resultant anthropometric statistics. The sample size is partially determined by the confidence needed at specific points on the distribution. In generic sample design, the target is often 90 or 95 percent of the user population. In this paper, alternatives to traditional design targets are identified, and the effects of these different approaches to sampling and design targets are discussed.

11. ALTERNATIVE APPROACHES TO SAMPLING FOR ANTHROPOMETRIC STUDIES OF PERSONS WITH DISABILITY

JAMES A. LENKER & VICTOR L. PAQUET

Two approaches are presented for framing population samples in anthropometric studies of persons with disability. One method is framing samples based on *type of mobility device used* by study participants, while the other is a sampling frame based on *functional level* of participants. Although both approaches have limitations, both methods merit further discussion for their potential value when anthropometric data are used by designers and policy makers.

12. NORMAL AND MAXIMUM REACH MEASURES OF WHEELCHAIR MOBILE ADULTS

JOHN W. KOZEY & BIMAN DAS

This research employed a direct anthropometric measurement approach to the study of the normal reach area (NRA) and the maximum reach envelope (MRE) of a sample of 42 male and 20 female, wheelchair mobile adults. The intended application of the research is to industrial workstation design. A computerized potentiometric system for anthropometric measures (CPSAM) was designed, built and tested for use in this study. The CPSAM recorded the position of a movable pointer in 3-D space with respect to a table reference point. The subjects were positioned in front of an adjustable work surface and asked to produce three trials of each of the desired reach types. Separate linear equations that mathematically represent the 3-D reaching boundaries were derived to describe the 5th, 50th and 95th percentile reach boundaries for males and females, separately.

13. ANTHROPOMETRICS IN WHEELCHAIR MOBILITY STUDIES

ALICIA M. KOONTZ, RORY A. COOPER, & LINDA VANROOSMALEN

Anthropometrics and ergonomics are essential for understanding the interaction between the wheelchair user, wheelchair and environment. At the Human Engineering Research Labs (HERL), anthropometric measures have been collected on over 60 manual wheelchair users. This information has been used to define input parameters for biomechanical models of the upper limbs, to investigate body mechanics during daily wheelchair mobility, and to develop guidelines and products for optimizing the fit of the user to the wheelchair. Relationships have also been discovered between wheelchair occupant anthropometrics and the biomechanical variables associated with secondary injuries in the upper extremities of manual wheelchair users. This paper discusses the role of anthropometrics in recent wheelchair mobility studies.

14. DETERMINATION OF NEW DIMENSIONS FOR UNIVERSAL DESIGN CODES AND STANDARDS WITH CONSIDERATION OF POWERED WHEELCHAIR AND SCOOTER USERS

LAURIE RINGAERT, DAVID RAPSON, JIAN QIU, JULIETTE COOPER, & EDWARD SHWEDYK

While universal design strives to create environments that are usable by everyone, building codes, standards, and guidelines have not yet considered the needs of users of powered mobility devices such as scooters and power wheelchairs. This is one of the first studies to examine the relationship of anthropometry, device dimensions and function in simulations of environmental conditions. The goal of this study was to identify possible changes that should be made to pertinent sections of codes and standards (particularly Canadian Standards Association CAN/CSA-B651-95 and to the Canadian National Building Code Section 3.8) that would take into account the requirements of powered wheelchair and scooter users.

The methods used to collect the data included: 1) face to face interviews to collect demographic information and a questionnaire of problems the participants encountered while using their devices in indoor and outdoor built environments, 2) measurement of the participants' devices and reaching capabilities, 3) environmental simulation of pertinent sections of codes and standards. Measurements were recorded via direct measurements with tape measures as well as by overhead video recording of some of the simulations.

Changes to codes/standards are recommended in all areas studied. Mobility device dimensions need to be generally increased. Many reach requirements need to be increased (e.g., low reach) while others should be decreased (e.g., far reach). Increases are recommended for the 360 degree turn, width path of travel, depth and width of ramp landings, and the space required in front of doors. Implications of these recommendations to particular areas of codes and standards are presented in the text and in a table.

15. BATHING NEEDS OF OLDER ADULTS WITH MOBILITY DISABILITIES

JON A. SANFORD

Accessibility guidelines for bathing fixtures are primarily based on the capabilities of adult wheelchair users who transfer directly to a fixture. However, findings from a national survey of almost 1200 individuals suggest that these guidelines may not be applicable for older people whose functional abilities, preferences, and transfer techniques differ from those of younger adults. Data from a subsample of 777 respondents age 55+ suggest that older people need assistance with sit-to-stand movements as well as in-fixture seating due to difficulty standing for extended periods of time. The typical tub/shower combination (with or without a transfer seat) was the most difficult fixture to use even with grab bars that met ADA requirements. Overall, respondents had less difficulty using fixtures with a seat than without one. In fact, they reported less difficulty using a bathtub with a seat than a roll-in shower without a seat.

16. THE IMPACT OF SOCIAL ADAPTATION ON FEMALE POST-REPRODUCTIVE FRAILTY

SHARON HEWNER

Understanding the impact of cultural factors on successful completion of everyday tasks can contribute new perspectives to anthropometry. This paper uses anthropological research on frailty to demonstrate how qualitative data can be used to define measurable outcome variables. Differences in female frailty in old age are related to both biological and cultural patterns. In order to understand the impact of culture on health, it is essential to go beyond individual life style or dietary habits, to include household characteristics that influence health. Household production of health has been a useful concept in medical anthropology. It focuses attention on cultural factors in the home that support the health of individual members. Within a given community there is a continuum in household production of health from behavior that limits the health of household members to highly supportive behavioral patterns. In an effort to understand the variability of household health in communities with clear cultural boundaries, the author developed a five-point scale of household health.

Outcome measures used in anthropometry such as "comfortable reach" can be developed using qualitative methods that give the research population a voice in defining the measure themselves. Moreover, it is important to understand the differences in that definition for biological-culture groups such as older frail women.

17. AN INTRODUCTION TO MULTI-SENSOR DATA FUSION

JAMES LLINAS

Multisensor data fusion is an emerging field involving a wide variety of advanced methods of information processing. It is typically implemented within a framework of automated aids to analysis and decision making. It originated in the military applications of surveillance and reconnaissance in which streams of data from many different sources are applied to observe a common space or volume. Such methods have also been used extensively in non-military applications such as monitoring complex machinery, medical diagnosis, intelligent transportation systems, smart buildings and robotics. This paper provides a tutorial on multisensor datafusion introducing illustrative applications, process models and techniques. It provides an introduction to a technique that could have significant application in the field of anthropometry in two ways: 1. integrating several streams of information collected on the same phenomenon, e.g. exertion data and kinematic data and 2. integrating data from different studies on the same issues.

18. CREATING DESIGN TOOLS FROM FUNCTIONAL ANTHROPOMETRY DATA

MATTHEW P. REED, PH.D.

Advancements in anthropometric data collection technology, including posture tracking and three-dimensional scanning, provide the opportunity to create much larger and more complete anthropometric databases than were feasible in the past. However, these databases are generally not, by themselves, of any value to product and workstation designers. In the past, data from anthropometric surveys have been organized at a very high level of abstraction into tables. Printed tables of percentile values, for example, are the sole access most designers have to standard anthropometric data sets. Functional databases, such as maximum reach envelopes, have been similarly abstracted to a set of planar percentile curves presented in design handbooks.

The human modeling software now used to design products and workstations provides a platform that can be used to deliver a much richer and more powerful set of anthropometric tools. This emerging technology presents three interrelated challenges: (1) developing flexible, powerful, and easy-to-use approaches to access the results of anthropometric studies; (2) designing and conducting anthropometric studies to gather the needed information; and (3) educating the user population so that they can apply the new models effectively. This paper addresses these challenges with respect to the anthropometrics of disability.

19. THE NEED FOR A SIMPLE AND TRANSPARENT TEMPLATE FOR HUMAN MODELING IN 3D

JOAKIM ERIKSSON

Recent developments in consumer-oriented 3D-graphics have opened up possibilities for a wide range of applications using computer-based manikins. Unfortunately, the information needed for designing manikins with high levels of anthropometric and biomechanic accuracy and realism is scattered and sometimes proprietary. There is also no consistent nomenclature for 3-D applications. This article describes a simple, transparent manikin "template", based on a common spreadsheet format. Intended areas of application are primarily within a 3D-graphics context, either when designing manikins with an existing 3D-modeling/CAD package, or when developing programs that produce manikins. While the suggested template in its present form has several limitations and crude approximations, the aim is to provide an “open source” approach that anyone can adopt to make improvements and additions (similar to LINUX and other open source software projects). It has been implemented as a simple spreadsheet document (Microsoft Excel) so that it is transparent and accessible for improvements.

20. FULL SCALE MODELING AS AN ANTHROPOMETRIC RESEARCH METHOD

EDWARD STEINFELD

Traditional anthropometric research has relied on measurements of the body and functional ability to develop databases for design. In the design fields, however, this approach has resulted in some significant gaps in our knowledge about how people with disabilities interact with their environment. In particular, most environmental design projects focus on specific and unique body movements and postures in and around constrained spaces. The data provided by traditional approaches cannot always be applied directly to these problems. Full-scale modeling can be used to measure functional abilities in context. Successfully used in the aerospace and automotive industry, this method provides a needed complement to the conventional anthropometric surveys that have been performed in the past.