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ABSTRACT Space requirements for accommodating wheeled mobility devices and their users in the built environment are key components of standards for accessible design. These requirements typically include dimensions for clear floor areas, maneuvering clearances, seat and knee clearance heights, as well as some reference dimensions on wheeled mobility device sizes. Recent research from four countries was reviewed and compared with their prevailing accessibility standards to identify needs for improving standards. Findings from ongoing anthropometry research on wheeled mobility in the U.S. were used for evaluating the adequacy of existing U.S. accessibility standards. Preliminary analysis suggests that the U.S. standards, which are based on research conducted in the 1970s, need to be updated to address advances in wheeled mobility technology and changes in user demographics. The analysis highlights the importance of integrating research with standards development, organizing international collaborations, and developing international standards.

KEYWORDS accessibility, anthropometry, standards, wheeled mobility

INTRODUCTION

The standards used to ensure accessibility for people who use wheeled mobility devices such as wheelchairs and scooters are based on research in anthropometry, the measurement of body sizes and physical abilities. The anthropometric data on wheeled mobility users that formed the basis for the technical requirements of the ANSI A117.1 standard (ANSI, 1980) and the Americans with Disabilities Act (ADA) Accessibility Guidelines (ADAAGs) (U.S. DOJ, 1994) were generated from research completed from 1974–1978 using a sample that included about 60 individuals who used wheelchairs (see Steinfeld et al., 1979).

In 25 years, many changes have occurred in the body sizes of the U.S. population, the demographics of people who use wheeled mobility devices, and the characteristics of equipment that they use. Yet, the standards have not changed. In fact, until recently, a newer anthropometric data set on wheeled mobility users in the U.S. was not available. In response to this lack of current information, the Center for Inclusive Design and Environmental Access (IDEA Center) has been developing a comprehensive data set with a high level

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of accuracy (Feathers, Paquet, & Drury, 2002, 2004; Paquet & Feathers, 2004). Although data collection is ongoing, we have now achieved a sample size and breadth that we believe is sufficient to start a dialogue about the need for revision of the current standards.

Comparisons of international standards and research are useful to validate methods and confirm results. They are also useful to identify best practices and differences related to cultural factors. In this article, we present a comparative analysis of research and standards on wheeled mobility in the U.S., the U.K., Australia, and Canada. The analysis presented here is limited to wheeled mobility device dimensions, minimum clear floor areas, space requirements for maneuvering, seat height, and knee clearance height.

METHODS

Document Analysis

We reviewed ICC/ANSI A117.1 (1998) Accessible and Usable Buildings and Facilities, which serves as the model for the technical requirements in the federal guidelines in the U.S., and the ADAAGs (U.S. DOJ, 1994) and their eventual replacement, the Americans with Disabilities Act Architectural Barriers Act Guidelines (ADA-ABA) (U.S. Access Board, 2004). For the U.K., we reviewed BS8300:2001 Design of Buildings and Their Approaches to Meet the Needs of Disabled People–Code of Practice. For Canada (CA), we reviewed B651-04 Accessible Design for the Built Environment. For Australia (AS), we reviewed AS 1428.2–1992 Design for Access and Mobility Part 2: Enhanced and Additional Requirements–Buildings and Facilities.

Since the findings of anthropometric research are often voluminous, journal articles and book chapters do not usually include a full documentation. We identified, through professional contacts, the standards and research completed in each country since 1980, the year after the research of Steinfeld et al. (1979) was published, and any research that was completed as a basis for those standards. Original research reports from the studies conducted outside the United States were obtained, namely Ringaert et al. (2001) from Canada, Hitchcock et al. (2006) and Stait et al. (2000) from the United Kingdom, and Bails (1983a, 1983b) and Seeger et al. (1994) from Australia. The research underlying BS8300:2001 in the U.K. was summarized in an annex to the U.K. standard itself, but we were unable to obtain a more comprehensive report that described the details of the methodology. The IDEA Center research findings were also tabulated for the comparisons.

Variable Definitions and Comparative Analysis

We compared standards and research studies to identify common underlying anthropometric variables. Our analysis then focused only on these variables. This task required us to make some assumptions and introduce qualifications since the four standards did not include the same variables, terminology, or measurement conventions. For example, the U.S. standards include both Imperial units and "soft" conversions (Imperial units rounded off to the nearest 5 mm) to metric units, but all of the other standards are in metric units only; in addition, there are at least three different terms used for a "wheelchair turning space." These differences present several problems in making comparisons. For example, the definition of a wheelchair turning space determines the experimental protocol used to study the clearance needed. Different results are obtained if that space is bounded or unbounded, and differences also occur when the measurement protocol calls for a smooth continuous turn, includes a series of smaller movements, or allows either. Since the standards do not define variables clearly, researchers have used different protocols to study the same variables. Thus, to make comparisons, we standardized all of the values from standards and research as much as possible based on a common definition of variables and measurement conventions. We calculated the U.S. values in both Imperial and metric units but did not convert the other countries' values to Imperial, nor did we convert the U.S. Imperial values to precise metric values.

The research studies reviewed also used different approaches to reporting their findings. Some results were reported in percentiles, often 5th and 95th percentile values, while a few studies provided 80th and 90th percentile values. Some results were reported as minimum or maximum values. Still others were reported as "percentage of subjects accommodated." This could imply that, rather than taking measurements of the individual or a minimum clearance space, researchers recorded only the ability to perform a task at a certain criterion level or whether an anthropometric dimension value was less or greater than a certain criterion value. For purposes of the current analysis, we assumed that the "percentage of subjects accommodated" was derived from the percentile value of the corresponding anthropometric dimensions. For instance, in the case of clear floor area (a rectangular area typically derived from the occupied width and length of mobility devices), the clear floor area width *accommodating 90% of the study sample* reported in the annex to the UK BS8300:2001 study is compared with the *90th percentile value for occupied width* obtained from the IDEA Center study. Some studies focused on a very limited set of variables. Because of the methodology used in the IDEA Center anthropometry research, however, we were able to compute results for all of the variables and all relevant statistics. Thus, our results appear in all of the analyses and can be compared to each of the standards included in this review.

A graphical method was used to compare the results of the research studies to each other and to the standards. Most of the studies reported at least a minimum or maximum value and a mean value for each variable studied. These three points were displayed on a graph and coded by study. Where available, percentile data were added to the graph in between the minimum and maximum values and the mean to provide more detail. Due to reasons of conciseness, for the dimensions where measurements were available from more than one research study in a particular country, only the most recent study was included in the comparison. However, detailed comparisons among all of the studies on the eight reported dimensions and several others are available in an online report (see Steinfeld, Maisel, Feathers, & D'Souza, 2010).

RESULTS

A summary of the main differences in the research studies reviewed, based on samples recruited, measurement methods employed, and data reporting formats, is presented in Table 1. Dimensional criteria prescribed in the accessibility standards from Australia, Canada, the U.K., and the U.S. are compiled in Table 2 for eight key design variables: unoccupied mobility

TABLE 1 **Comparative summary of the research studies reviewed**

Study	Sample	Methods	Reliability	Scope
Bails, 1983, AUS	Total unknown, manual and power chairs, from institutions	2-D, manual	Not reported	Body and device size, reaching, maneuvering, door use
Seeger et al., 1994, AUS	240, all devices, 75% from institutions	2-D, manual measurements	Not reported	Body and device size
DETR: Stait et al., 2000, U.K.	745, all devices, attendees at Mobility Roadshow	2-D, photography with digital measurements	Reliability study completed and reported	Body and device size
BS8300: 2001 appendix (research commissioned by DETR), U.K.	164, all devices, but only 91 for space allowances, source unknown	Not reported	Unknown	Body and device size, knee and toe clearances, reaching, maneuvering, door use
UDI: Ringaert et al., 2001, CA	50, power chair and scooter users, diverse sources	2-D, manual measurements, detailed interview	Not reported	Body and device size, reaching, maneuvering
DfT: Hitchcock et al., 2006, U.K.	1,356, all devices, attendees at Mobility Roadshow and 12 other sites	2-D, multi-image photogrammetry	Reliability study completed and reported	Body and device size
IDEA Center, 2010: Steinfeld et al., 2010, U.S.	369, all devices, diverse sources	3-D, digital probe, video, detailed interview	Reliability study completed and reported	Body and device size, reaching, maneuvering, door use

TABLE 2 Comparison of accessibility standards across four countries

Measurement dimension	Australia, AS 1428.2 (mm)	Canada,[a] B651-04 (mm)	U.K., BS8300:2001 (mm)	U.S., ICC/ANSI A117.1 (mm & in.)
	Country and standards document			
Wheelchair dimensions				
Unoccupied device width		660		660 (26)
Unoccupied device length				1,065 (42)
Clear floor area				
Width: minimum	800	750	900	760 (30)
Length: minimum	1,300	1,200	1,350	1,220 (48)
Heights				
Seat height: maximum	480	480		485 (19)
Knee clearance height: minimum	640–650	680	700	685 (27)
Maneuvering spaces				
90-degree turn		920		915 (36)
360-degree turn	1, 540 × 2, 070	1,500	1,500	1,525 (60)

[a]This standard also includes an appendix with information on device size and maneuvering spaces for power chairs and scooters derived from the UDI research.

device width and length, clear floor area width and length, seat height, knee clearance height, and maneuvering spaces for a 90-degree and 360-degree turn. To facilitate readability, Figures 1–8, comparing the standards and research findings for these eight variables, are provided in the subsequent section, wherein each variable is discussed in detail.

DISCUSSION

This section is divided into three parts. First, we present an overview of the reviewed anthropometry studies. Second, we highlight the main differences among these studies and their implications for the generalizability of research findings. Finally, the eight variables included in the comparative analysis are each discussed in turn.

Summary of Anthropometry Studies Reviewed

There were many differences among the studies reviewed. A short overview of each of the reviewed studies is presented to provide the context and possible reasons for these differences.

In his study, Bails (1983a, 1983b) recruited participants from attendees at disability support centers and institutions. Eligible participants were between 18 and 60 years of age and used a manual or powered wheelchair. Scooter users were not included in the study. The total sample size is not known. The research focused primarily on testing of full-size simulations of elements found in the built environment, such as doorways, environmental controls, furniture, and fixtures that were configured to meet the Australian standards at the time. Many of the findings, therefore, could not be used to make generalizations or to determine the ideal spaces needed for access.

Seeger et al. (1994) studied only device size. About 73% of the 240 individuals in the sample lived in nursing homes and other institutions. Forty-five percent were over 65 years old. Eleven percent used power chairs, and 2% used scooters. Both unoccupied and occupied dimensions of device width and length were measured as well as a set of other basic dimensions. Measurements were taken manually using conventional measuring tools, including a tape measure, steel square, and spirit level.

The Department of Environment Transport and the Regions (DETR) (Stait et al., 2000) and the Department for Transport (DfT) (Hitchcock et al, 2006) studies were the two most recent in a series of three large-scale wheelchair anthropometry surveys conducted in the U.K. The studies were limited to the measurement of device size and weight. The DETR survey, conducted in 1999, recruited participants solely at an exposition of equipment for people who use wheeled mobility devices for traveling around the community. The subsequent DfT survey was widened to include 12 schools and retail centers in the U.K., in addition to the 2005 Mobility Roadshow. Of the 745 participants in the DETR study whose data were acceptable, 59% used self-propelled manual chairs, 9% used attendant-powered chairs, 25% used power chairs, and 9% used scooters. Nine percent of the sample were reported to be 16 years of age or younger. The DfT study sample comprised 1,098 adults and 247 children. Among adults, 41% used self-propelled manual chairs, 10% used attendant-propelled wheelchairs, 27% used power chairs, and 22% used scooters. The DETR study used two photographs of each participant, while the DfT study employed seven photographs taken with a camera from predetermined angles after participants wheeled into position on a scale. A checkerboard pattern on the floor and wall provided references to take measurements off the photographs. Parallax was corrected during the calculation of the anthropometry dimensions. For each of these two studies, the reliability of the method was verified prior to data collection by comparing dimensions taken directly from individuals with those calculated from photographs. Device dimensions were defined clearly. Although a wide variety of accessories were observed on the devices, they were not measured as part of the width calculation.

The research used as a basis for revisions to the U.K. BS8300:2001 standards covered clear floor area space requirements, knee clearances, and maneuvering clearances. A total of 164 individuals were included in the sample, but only 90 participated in the research on space allowances. Due to the lack of a full research report, it is not clear how the measurements were collected and, in many cases, the landmarks used to define them. From the information available, it appears that some scooters and attendant-propelled chairs were included in the sample, but it is not clear whether these individuals were included in the reported device or body measurements.

The Universal Design Institute (UDI) study (Ringaert et al., 2001) included a sample of individuals recruited from disability and senior organizations in Winnipeg by written invitation. Of the 50 participants, 35 (70%) used power chairs and 15 (30%) used scooters. The cause of disability for individuals in the sample included a wide range of conditions. Device size and maneuvering spaces were measured. All dimensions were taken to the extremes of the equipment including any object attached to the device, such as a ventilator. However, the actual landmarks on the devices were not well documented. Measurements were made with rulers and tape measures, but no information was given on the accuracy and reliability of these techniques. Maneuvering trials were recorded using overhead video cameras while participants completed standardized movements in simulated environments built with plywood floors and wood framed dividers. Measurements were later taken off the videotapes, although the method used to extract the measurements and the reliability of the technique were not described. An observer rating was used to determine successful trials.

The IDEA Center study (Steinfeld et al., 2004, 2010; Feathers, Paquet, & Steinfeld, 2004; Paquet & Feathers, 2004) included static anthropometric measurements of occupied wheeled mobility devices, mobility device dimensions, and measurements of maneuvering clearances. At the time of preparing this report, 369 participants with a wide range of chronic conditions had been recruited through outreach efforts with several organizations in western New York and mass media. Fifty-eight percent of the sample was male and 42% female. The mean age of the sample was 52.4, with a range of 18–94 years. Fifty-three percent used manual wheelchairs, 39% used power wheelchairs, and 8% used scooters. Three-dimensional locations of body and wheelchair landmarks were collected with an electromechanical probe (Feathers, Paquet, & Steinfeld, 2004). Good reliability was achieved using trained staff (see results in Feathers, Paquet, & Drury, 2002, 2004). Maneuvering clearances were measured while participants conducted standardized maneuvers between a set of lightweight movable walls. The walls were gradually moved further apart in fixed increments until the maneuver could be completed without the participants moving the walls. Clearances were premeasured on the floor of the test site using tape and marker, and the locations of walls were recorded after each trial.

Comparison of Research Methods

Participant Recruitment and Sampling Issues

The studies reviewed utilized widely different methods to recruit participants. The DETR study conducted in 1999 had a large sample size, but the participants were all self-selected according to their interest in and ability to attend a "mobility roadshow," presumably an annual event. The roadshow is an exposition of mobility devices and related services with a focus on adapting automobiles and recreational pursuits. There may be some self-selection in the attendance based on car ownership, recreational interests, location, income, and other factors. The sample is likely to be more mobile and have higher incomes than the wheeled mobility population as a whole, and their choice of devices may reflect that. A high rate of unusable data due to problems with photography may have introduced some sampling bias as well, for example if data were unusable owing to a systematic reason related to characteristics of devices (e.g., very large devices being unable to fit in the frame of the photograph, obscured parts). While the DfT study (Hitchcock et al., 2006) relied similarly on recruitment of participants from the 2005 Mobility Roadshow, additional participants were recruited from 12 retail centers and schools to increase the representativeness of the sample. The Seeger and Bails samples were drawn primarily from institutional settings, which would definitely introduce bias in the types of devices used and maneuvering abilities. Both the IDEA Center and UDI studies recruited a diverse sample and provided transportation to the research site, ensuring that low mobility would not be a barrier to participation. However, in both cases, the samples could not be considered representative of the entire population of wheeled mobility users in their respective countries. Users of powered chairs were overrepresented in the IDEA Center study sample. The UDI study did not include manual wheelchair users at all.

The UDI and Bails studies had very small samples. Bails, in particular, had subsamples for some of his protocols that included as few as five individuals. A limitation of both the IDEA sample and the UDI sample is that they were drawn entirely from cold weather cities. This may have introduced some bias toward larger and more durable equipment. Data were collected all year round in the IDEA study, so season should not have introduced a bias in recruitment; however, the UDI study was conducted only in winter, which may have influenced participation.

Measurement Methods Description and Reliability

The methods used in the Bails and the U.K. BS8300 study were not reported in detail, rendering them difficult to evaluate. The reliability of measurements taken in the UDI and Seeger research is not known. It appears that UDI did not address issues of distortion caused by camera lenses in its analysis of some maneuvering trials. Both UDI and Seeger used rulers and tape measures rather than more accurate anthropometric instruments designed for such purposes. In the UDI research, the lack of a reliability study to determine the level of agreement among researchers to rate the level of "accessibility" observed is a key limitation because those ratings were used to determine success in managing specific space clearances. In addition to the IDEA Center study, the DETR and DfT studies are also very well documented, and reliability studies were completed in the preparation phase.

The UDI research study (Ringaert et al., 2001) was focused on validating the B651-04 Canadian standard. All of the maneuvering trials started with the clearances in the standard, but the results of fitting trials can be influenced by the first set of conditions presented to the participant. In contrast, the IDEA Center research started with the smallest possible space. This decision was influenced by pilot tests in the preparation phase of the research during which we discovered that some test participants could manage maneuvers in much smaller spaces than the minimum clearances of the ADAAGs.

Presentation of Findings

Conveying information on sample size, participant eligibility criteria, and dropouts is an important aspect in anthropometry studies comprising fairly heterogeneous populations that differ in body size and functional capabilities. Most of the studies were actually a collection of smaller "substudies" focusing on one or more measures that utilized different subsamples drawn from the larger study sample. Additionally, some study participants were excluded from the analysis of a particular variable due to their inability to perform a task (e.g., completing a 360-degree turning maneuver without assistance) or a measurement being unrecordable (e.g., knee height listed as "missing data" for participants with above knee amputations). Thus, the subsample for a particular variable could differ greatly from the total sample size in the study. For example, only 247 participants from among the 369 IDEA Center study sample were capable of performing a 90-degree turning maneuver without assistance. In the case of the 360-degree turning measurements, this number dropped to 215 participants. Details regarding subsamples for each of the measured variables in the IDEA Center study are provided in the full version of this report (see Steinfeld et al., 2010). Lack of relevant detail made identifying the total sample size across the measured variables in some of the other studies difficult.

The DETR, DfT, UDI, and BS8300 (U.K.) researchers provided results in percentile form. Findings from the IDEA Center study were also presented using percentiles. This is very valuable for making decisions about dimension values for use in standards because policymakers can easily use the data to determine the percentage of the population that could potentially be accommodated when assigning a value to a particular design dimension. At the very minimum, sample means and standard deviations should be provided so that all percentiles can at least be estimated. UDI, Bails, and the BS8300 researchers did not provide any information on whether outliers were identified and eliminated from the data reported or how outliers were defined. This information is very important for interpreting results.

Comparison of Anthropometry Variables

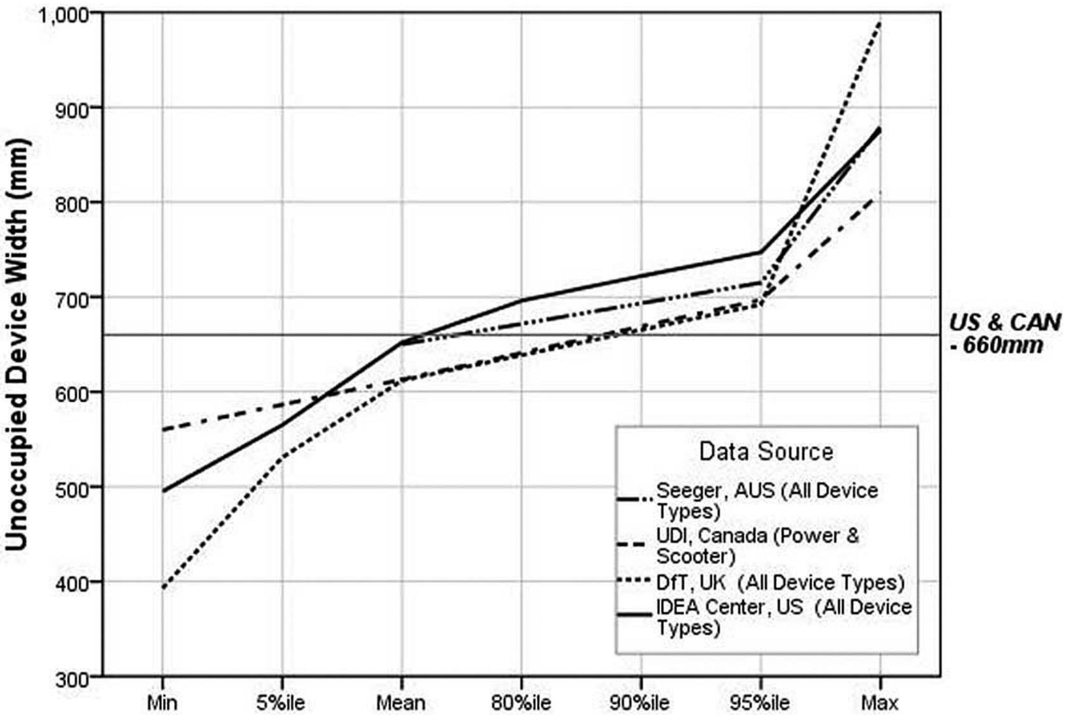
In this section, selected anthropometric variables are addressed individually. First we compare the standards on each variable, along with comparisons with research findings from the most recent study from each of the four countries (i.e., Australia, Canada, U.K., U.S.). For each variable, an accompanying figure provides a graphical comparison of results pooled across the entire study sample that highlight the finding that current standards do not accommodate a significant proportion of the samples in these studies. However, it is important to note that data pooled across the entire study sample (i.e., all mobility devices combined) can confound comparisons across studies due to differences in the proportion of manual wheelchairs, power wheelchairs, and scooters. The tabular data stratified by mobility device type are better suited for between-study comparisons. Also provided is a discussion on how this information can be used to identify needs for improving standards research.

Wheeled Mobility Device Dimensions

The research data show that the sizes of devices vary considerably from the values in the standards (Figures 1 and 2). The sizes described in the standards are closer to the mean values found in the research studies, but this is certainly not sufficient to accommodate a large enough proportion of wheeled mobility users. For example, the IDEA data for mean unoccupied width and length are identical to the U.S. standard reference wheelchair. But the widest device measured was about 225 mm wider and the longest more than 420 mm longer than the U.S. standard's "reference wheelchair." The data on wheelchair dimensions currently provided in the U.S. standards and generally accepted by the other countries were derived from manufacturers' data in the 1970s and did not include accessories that are often used with a device. Moreover, people with much more severe disabilities are now more mobile and independent (e.g., those dependent on ventilators).

To provide realistic guidance for designers, information on wheeled mobility dimensions should include occupied sizes as well as device size, both in percentile form, and should also include accessories as they are used in everyday life. Occupied device sizes are clearly preferable and more useful for designers than unoccupied sizes but are not uniformly provided in the standards. For example the U.S. standards are inconsistent, showing occupied length but unoccupied width. Although data on device sizes are available from manufacturers, they do not include actual dimensions as set up for individuals, nor are data provided on added equipment like seating systems, cushions, control boxes, ventilators, carrying baskets, and other accessories. The studies reviewed here did not always include accessories as part of their dimensions and measurements (e.g., Stait et al., 2000; Hitchcock et al., 2006).

The illustrations used to depict wheeled mobility devices in the U.S. standards, AS 1428, and BS8300:2001 are manual wheelchairs. The Canadian standard, however, includes illustrations and data on scooters and power chairs. This information can be very valuable to designers who are seeking to ensure full accessibility beyond minimum required levels. Additional illustrations are needed to convey the diversity in the devices and their occupants. Designers could also benefit from more information on device size to plan spaces such as storage areas for wheelchairs at transportation terminals or the design of counter edges in relationship to armrests. Accurate and reliable data on device size may be more appropriate to provide in a reference



Data Source	Sample Size	Min	5%ile	Mean	80%ile	90%ile	95%ile	Max
Seeger et al, AUS								
All Device Types*	240	-	-	650	-	-	715	880
UDI, Canada								
Power chairs and scooters*	50	560	-	613	-	-	697	810
DfT, UK								
Self-Propelled Wheelchair	458	393	572	635	-	-	707	992
Attendant-Propelled Wheelchair	106	505	538	595	-	-	662	719
Electric Wheelchair	294	399	536	605	-	-	670	745
Electric Scooter	240	426	478	579	-	-	669	840
All Device Types*	1098	393	531	612	-	-	692	992
IDEA Center, USA								
Manual chairs	195	509	571	660	698	722	740	876
Power chairs	146	539	562	644	672	726	760	845
Scooters	28	495	514	638	700	727	745	759
All Device Types*	369	495	565	652	696	722	747	876

* indicates data plotted in the graph

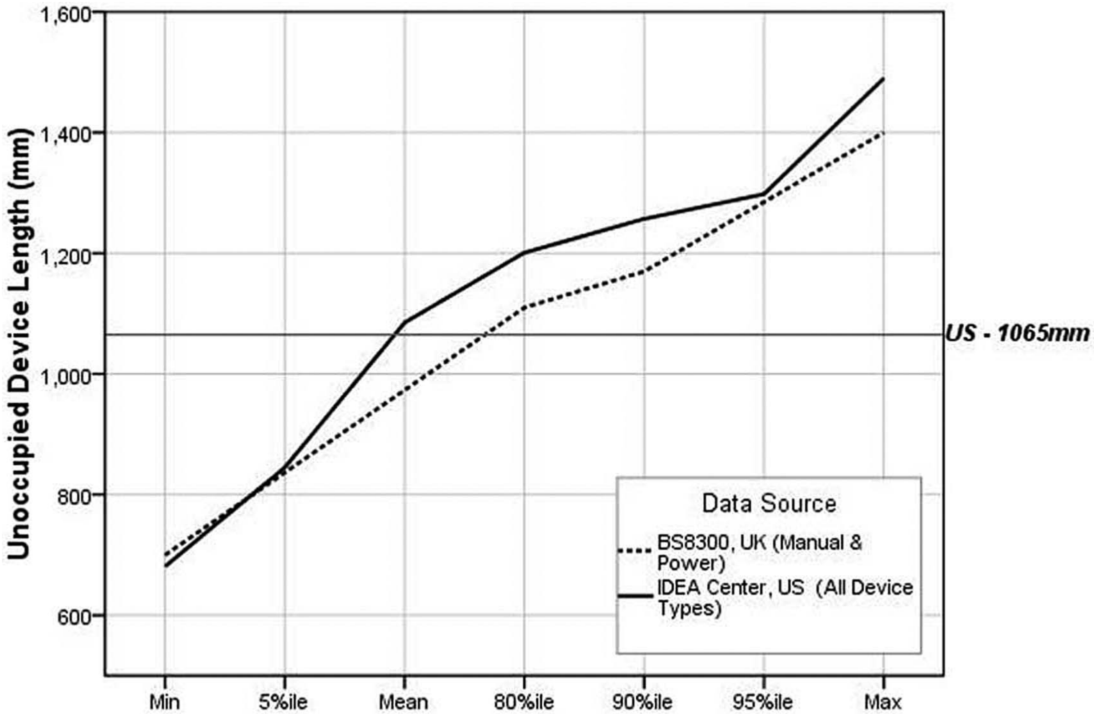
FIGURE 1 **Comparison of unoccupied device width in mm. Graph shows comparisons across studies for all mobility devices combined.**

manual that can include detailed information and extensive illustrations of different equipment types in use.

Clear Floor Area Width and Length

Recent revisions to standards in Australia and the U.K. increased the required clear floor area dimensions in both width and length. The U.K. requirements, in particular, are much larger than those in the U.S. and Canada. Research results support larger dimensions. All of the studies found that wheeled mobility devices vary from the standards significantly in both width and length. While there are many occupied devices that are narrower and shorter than the values in the standards, the largest devices are generally above the minimum width and length in the standards.

The findings on clear floor area are based on the findings on occupied width and length, where



Data Source	*Sample Size*	*Min*	*5%ile*	*Mean*	*80%ile*	*90%ile*	*95%ile*	*Max*
BS8300: 2001 Annex E, UK								
Manual chairs - self propelled	54	700	-	-	1090	1124	-	1200
Power chairs	27	700	-	-	1160	1190	-	1400
Manual and Power chairs*	81	700	-	-	1110	1170	-	1400
Electric scooters	5	1170	-	-	-	-	-	1500
IDEA Center, USA								
Manual chairs	195	685	790	1044	1173	1202	1241	1490
Power chairs	146	681	917	1116	1240	1275	1313	1449
Scooters	28	1044	1044	1212	1294	1384	1435	1439
All Device Types*	369	681	845	1085	1201	1257	1298	1490

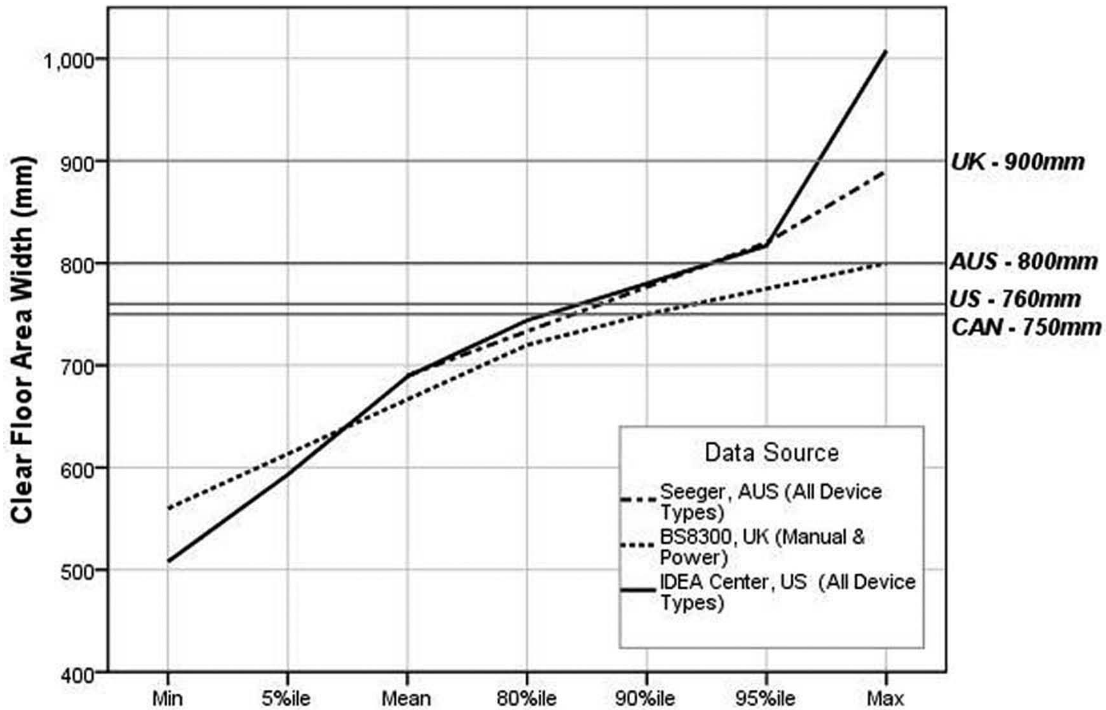
* indicates data plotted in the graph

FIGURE 2 Graphical comparison of unoccupied device length in mm. Graph shows comparisons across studies for all mobility devices combined.

provided (Figures 3 and 4). Neither the DfT nor the DETR study collected data on occupied width, but they did measure unoccupied device width. The authors argued that individuals can bring their arms and legs inboard when entering transportation vehicles and passing through doorways. We found, however, that many individuals do not have the physical ability to position their upper and lower extremities "inboard." Moreover, in situations where individuals might remain stationary for a relatively long time, for example at a concert or sporting event, it is unrealistic to assume that they would keep their upper and lower extremities in such a constraining position.

The BS8300 research did not report occupied widths larger than 800 mm, but the BS8300 standard, as we interpret it, requires 100 mm more than that for the clear floor area width (900 mm). The BS8300 standard's developers may have added 100 mm to provide additional maneuvering room at clear floor areas. However, the IDEA Center research did observe a significant proportion of occupied widths greater than the U.S. standard of 760 mm across manual chairs, power chairs, and scooters.

The largest occupied lengths all exceeded the current standards, even the U.K. BS8300 standard of 1,350 mm. However, the results show that the 95th percentile values are between 1,250 and 1,480 mm. The differences between the maximum length in the UDI and Seeger studies and the others are so great that they are probably due to the presence of unusually large people and/or devices or to measurement error. The maximum length (occupied) recorded in



Data Source	Sample Size	Min	5%ile	Mean	80%ile	90%ile	95%ile	Max
Seeger et al, AUS								
All Device Types*	240	-	-	690	-	-	820	890
BS8300:2001 Annex E, UK								
Manual chairs - self propelled	54	560	-	-	696	720	-	800
Power chairs	27	560	-	-	750	760	-	800
Manual and Power chairs*	81	560	-	-	720	750	-	800
Scooters	5	630	-	-	-	-	-	700
IDEA Center, USA								
Manual chairs	195	508	595	681	724	754	782	932
Power chairs	146	574	605	707	765	805	828	1008
Scooters	28	540	540	650	737	818	840	857
All Device Types*	369	508	593	689	744	780	817	1008

* indicates data plotted in the graph

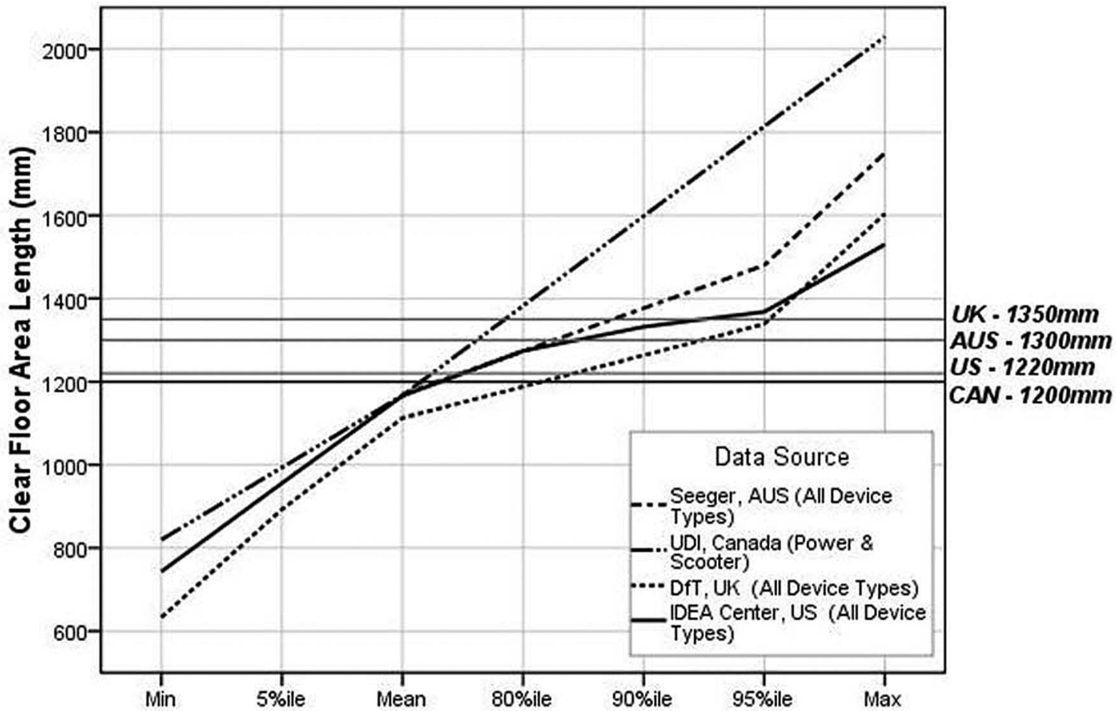
FIGURE 3 **Graphical comparison of clear floor area width in mm. Graph shows comparisons across studies for all mobility devices combined.**

the UDI study, for example, was over 2,000 mm (over 6 ft, 8 in.)! In the case of Seeger et al.'s work, we know that most of the sample was recruited from institutions, and many may have had extended footrests or reclined backs on their chairs. No information is provided in the reports to assess whether individuals in either study could be considered outliers. For example, since the other studies together included more than 1,200 individuals and no other study reported a device as long as 2,000 mm, such a large value is likely a measurement error or a very rare occurrence. In fact, by coincidence, we met an individual who served as an advisor and participant in the UDI research. She recalled that there was one individual who had a "trailer" attached to her wheelchair that carried ventilator equipment that most likely would not be required today due to advances in technology.

Seat Height

The values in the current standards for seat height are below the means for people measured in the IDEA Center and UDI studies (Figure 5). This is probably due to the increasing use of positioning systems, thick cushions, and the availability of a wider range of wheel sizes since the 1970s.

The reference points used for measurement can also yield quite different results for seat height. The



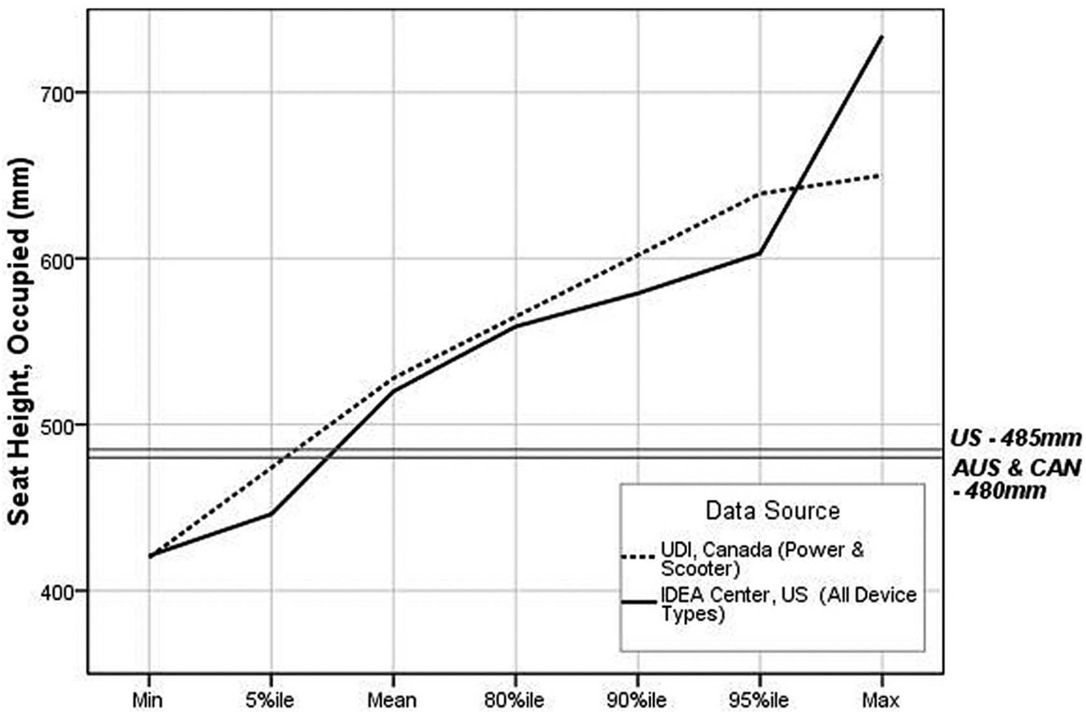
Data Source	Sample Size	Min	5%ile	Mean	80%ile	90%ile	95%ile	Max
Seeger et al, AUS								
All Device Types*	240	-	-	1170	-	-	1480	1750
UDI, Canada								
Power chairs and scooters*	50	820	-	1167.57	-	-	-	2030
DfT, UK								
Self-Propelled Wheelchair	458	776	864	1068	-	-	1254	1534
Attendant-Propelled Wheelchair	106	951	1003	1123	-	-	1344	1375
Electric Wheelchair	294	633	955	1142	-	-	1339	1604
Electric Scooter	240	828	956	1168	-	-	1416	1503
All Device Types*	1098	633	893	1113	-	-	1339	1604
IDEA Center, USA								
Manual chairs	193	743	918	1137	1233	1291	1334	1530
Power chairs	146	831	981	1196	1305	1352	1399	1487
Scooters	28	1044	1044	1212	1294	1384	1435	1439
All Device Types*	367	743	956	1166	1274	1332	1368	1530

* indicates data plotted in the graph

FIGURE 4 **Graphical comparison of clear floor area length in mm. Graph shows comparisons across studies for all mobility devices combined.**

height of the seat can be measured at the edge and at the middle, under the cushion, on top of the cushion, and so forth. Thus, specifying exactly how it is measured is important for comparing results. The IDEA Center study computed occupied seat height by measuring a point underneath an individual's buttocks using an extension of the electromechanical probe that we slipped in from the side between the occupant and seat interface. Our results would clearly be different compared to other measurements.

Height dimensions for seats prescribed in the Australian, Canadian, and U.S. standards were very similar. Comparisons of research findings on the seat heights for power chairs and scooters showed that mean seat heights measured in the UDI study were comparable to seat heights for power chairs and scooters in the IDEA Center study; however, the differences grew larger toward higher percentiles. The IDEA Center study findings also revealed that occupied seat heights for manual chairs were much lower than seat heights for power chairs and scooters.



Data Source	*Sample Size*	*Min*	*5%ile*	*Mean*	*80%ile*	*90%ile*	*95%ile*	*Max*
UDI, Canada								
Power chairs and scooters*	50	420	-	527.71	-	-	639	650
IDEA Center, USA								
Manual chairs	195	421	441	500	534	548	570	608
Power chairs	146	436	468	541	573	600	630	734
Scooters	28	472	478	553	582	593	637	643
All Device Types*	369	421	446	520	559	579	603	734

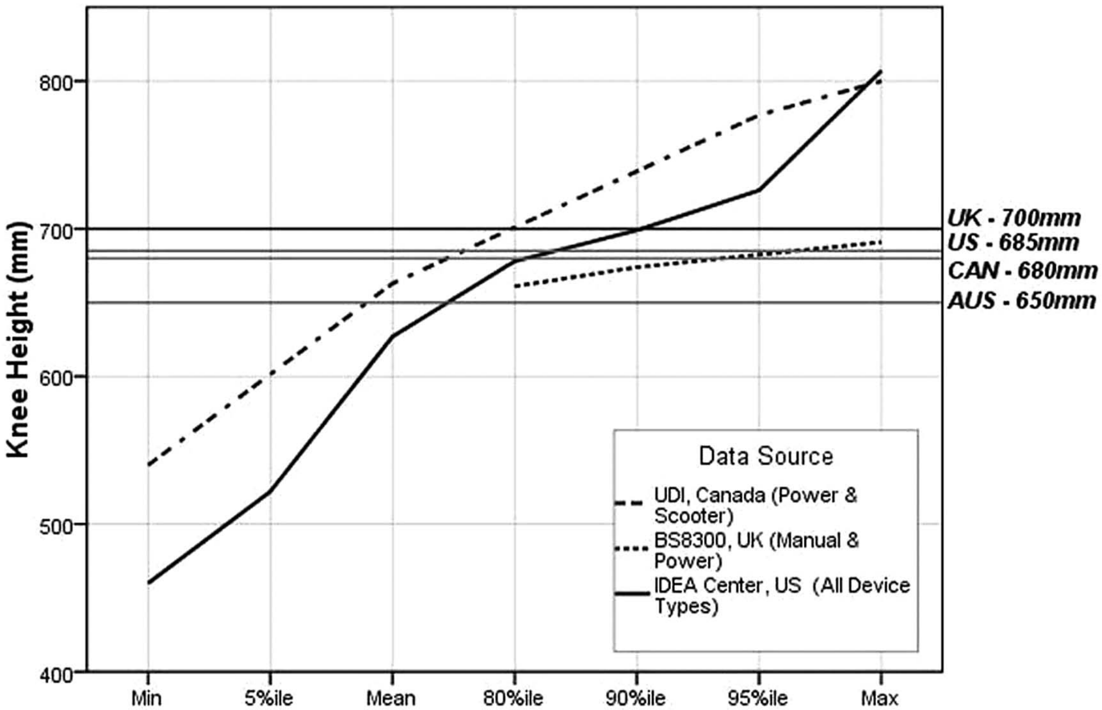
* indicates data plotted in the graph

FIGURE 5 **Graphical comparison of occupied seat height in mm. Graph shows comparisons across studies for all mobility devices combined.**

Knee Clearance Height

Knee clearances of the four sets of standards are roughly comparable (Figure 6). The U.K. BS8300 results for knee clearance height suggest that current U.K. standards generally accommodate most wheelchair users in that country. In the case of the U.S. and Canadian standards, however, the level of accommodation drops to 80% in relation to measured knee heights among wheelchair users in their respective countries. A review of photographs of participants in the IDEA sample indicates that the largest individuals are not always the ones who need the greatest knee clearances. Smaller individuals who have large thighs, those with high seats, and scooter users also have high lap heights. Individuals with extended footrests and scooter users have deep knee clearances but not necessarily high knee clearances. Thus, to develop design standards for providing sufficient legroom, it may be more relevant to analyze knee and toe clearances and depths together in a multivariate form rather than as individual univariate distributions.

It is clear that those people who need the highest knee clearances cannot be accommodated without making some radical changes to the design of counters, drinking fountains, and other design features where knee space is provided. Policymakers have to make a decision about who should be accommodated by knee clearances or require alternatives such as providing sideway access as well as front access. The results clearly provide evidence that adjustable and adaptable counters are a valuable design strategy. They suggest that more emphasis should be placed on adjustability, especially in home environments, and that the range of adjustability should be fairly large.



Data Source	Sample Size	Min	5%ile	Mean	80%ile	90%ile	95%ile	Max
UDI, Canada								
Power chairs and scooters*	50	540	-	663	-	-	777	800
BS 8300:2001, UK								
All Device Types*	164	-	-	-	661	674	691	-
IDEA Center, USA**								
Manual chairs	188	460	511	606	657	677	698	743
Power chairs	146	504	543	645	686	708	730	807
Scooters	27	553	563	667	711	754	776	785
All Device Types*	361	460	521.75	626.5	678	699	726	807

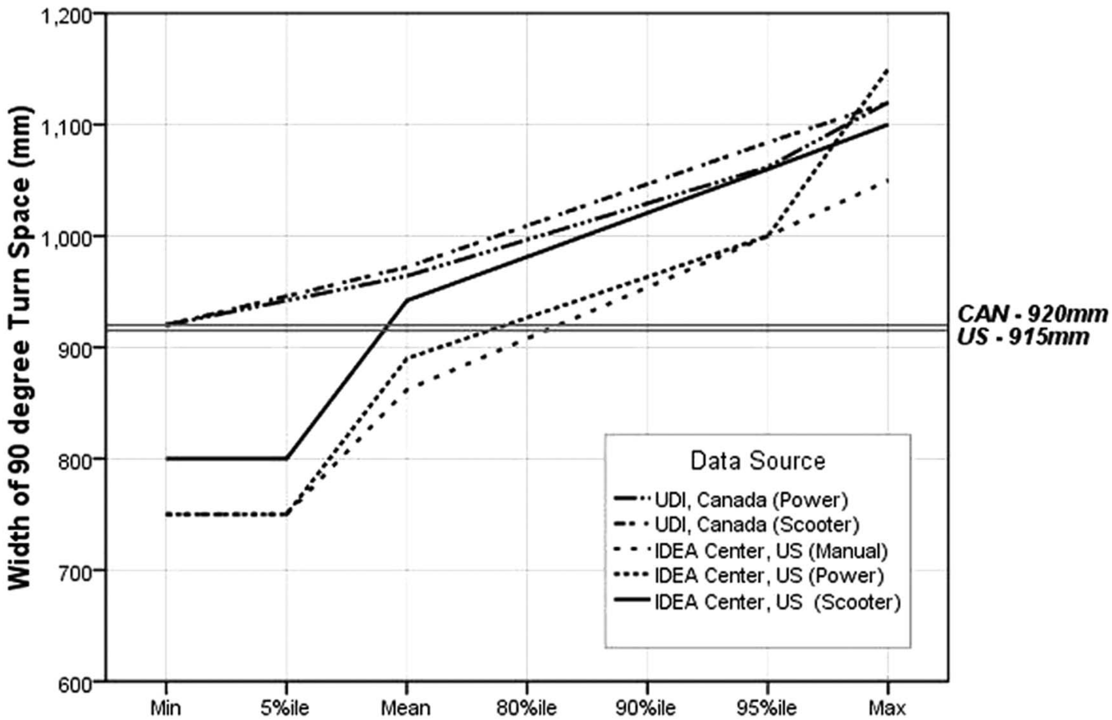
* indicates data plotted in the graph
** does not include individuals with an above-knee right leg amputation

FIGURE 6 **Graphical comparison of knee clearance height in mm. Graph shows comparisons across studies for all mobility devices combined.**

Maneuvering Clearances

Only the U.S. and Canada have requirements for 90-degree or L-turn clearances. All of the standards have requirements for "wheelchair turning spaces." Canada includes guidelines for both a 360-degree turn and a 180-degree turn. But it is not clear how these turns are defined. For example, when should one plan for a 360-degree turn as opposed to a 180-degree turn? Australia defines a rectangular area, whereas the other countries have adopted circular or "T-turn" geometries for depicting space requirements for maneuvering. Canada and the U.K. have added informative sections with more advisory information on maneuvering space requirements. These advisory data are based on the research reported in the UDI report and the BS8300 annex, respectively.

The clearance required for all participants to complete a 90-degree turn in the IDEA Center study sample was much smaller than the UDI findings (Figure 7). An increase in the clear width criterion of 100 mm (4 in.) would be needed to accommodate at least 95% of the IDEA sample. However, to accommodate the entire UDI and IDEA Center study samples, an increase of 250 mm (10 in.) would be needed. As in the case of the IDEA Center study results, the UDI findings at the high end of the range probably reflect the impact of a few participants or devices with very poor turning ability.



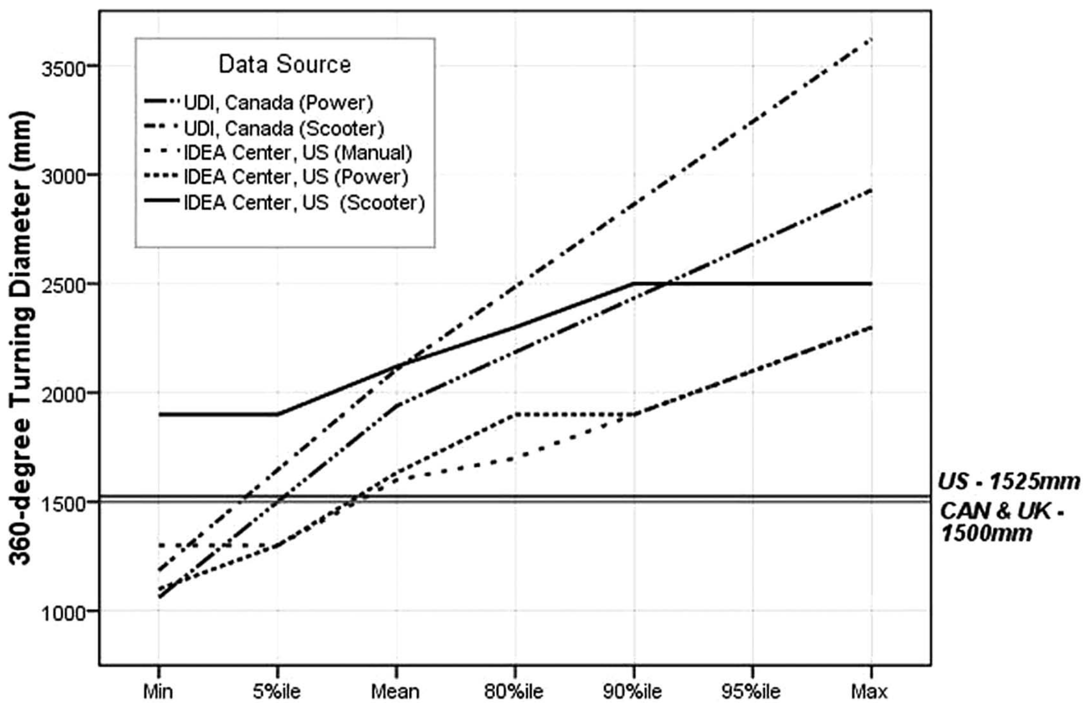
Data Source	*Sample Size*	*Min*	*5%ile*	*Mean*	*95%ile*	*Max*
UDI, Canada						
Power chairs - CW*	-	920	-	964	1062	1120
Power chairs - CCW	-	920	-	972	1084	1120
Scooters - CW*	-	920	-	1030	1158	1120
Scooters - CCW	-	920	-	1025	1145	1120
IDEA Center, USA**						
Manual chairs*	127	750	750	862	1000	1050
Power chairs*	107	750	750	890	1000	1150
Scooters*	13	800	800	942	1060	1100
All Device Types	247	750	750	878	1000	1150

* indicates data plotted in the graph
** does not include individuals that were unable to complete a 90-degree turn without assistance

FIGURE 7 **Graphical comparison of 90-degree turn width for all devices in mm.**

The IDEA Center research and the UDI study protocols included 360-degree and 180-degree turns. The BS8300 reported only the latter but did not define it. Comparisons of 180-degree turn spaces are provided in the full online report; only the 360-degree turn spaces are discussed here. The IDEA study results demonstrated that turning area clearances would have to be increased to 2,500 mm (98 in.) compared to the current 1,500–1,525 mm (60 in.) to accommodate the entire study sample (Figure 8). In comparison, the UDI participants utilized a much larger space for the 360-degree turn, in which no sides were blocked. A space of about 4,200 mm (165 in.) would be needed to accommodate the entire sample. In the IDEA sample, scooters required more space, but the largest values for scooters, power chairs, and manual chairs were very close, whereas in the UDI sample at least one power wheelchair user required a much larger clearance for the 360-degree turn (most likely the person with the "trailer").

The results support increasing the clearances for 90-degree turns and wheelchair turning space. However, it appears that there are some people at the tail of the distribution who require much larger spaces than the 95th percentile values. It is important to note that this group is composed of manual chair, power chair, and scooter users. More detailed information on these individuals and the size of their devices is needed. They may be very restricted in their abilities to maneuver chairs independently. We observed some manual



Data Source	Sample Size	Min	5%ile	Mean	80%ile	90%ile	95%ile	Max
UDI, Canada								
Power chairs - CW*	-	1062	-	1939	-	-	-	2929
Power chairs - CCW	-	1307	-	1957	-	-	-	2723
Scooters - CW*	-	1186	-	2107	-	-	-	3622
Scooters - CCW	-	1340	-	2128	-	-	-	3608
Power chairs and scooters - CW	41	1062	-	1997	-	-	3007	3622
Power chairs and scooters - CCW	37	1307	-	2022	-	-	2944	3608
IDEA Center, USA**								
Manual chairs*	109	1300	1300	1600	1700	1900	2100	2300
Power chairs*	96	1100	1300	1633	1900	2100	2100	2300
Scooters*	10	1900	1900	2120	2300	2500	2500	2500
Overall	215	1100	1300	1635	1900	2100	2100	2500

* indicates data plotted in the graph
** does not include individuals that were unable to complete a 360-degree turn without assistance

FIGURE 8 **Graphical comparison of 360-degree turning diameters for all devices in mm.**

wheelchair users who had very restricted push arcs. This limited their ability to maneuver a chair and resulted in wide turning circles.

The divergent UDI findings may be related to the lack of an enclosure in the 360-degree turn, errors in correcting for parallax when measuring from video cameras mounted above, or an inability to obtain accurate measurements of body parts and devices in motion.

CONCLUSIONS

The research reviewed here demonstrates that there is a need to revise the standards for wheeled mobility access to reflect the body structure and functional abilities of this population and the devices they use today. The U.S. standards are in more need of change, but the basis for many of the changes previously made to the standards in Canada, the U.K., and Australia can also be questioned in light of the research findings. Findings must be evaluated very carefully when used to make changes to standards. In particular, the impact of the methods used on findings needs to be studied in depth. Yet, the consistency of trends across the various samples is quite good, given the wide variety of methods used. The main problem in comparing findings is the lack of information about the extreme cases.

There is a clear need to develop an international consensus on both standards and research methods. In a global economy, people who use wheeled mobility devices can be expected to travel all over the world. At least in facilities that are frequented by international travelers, minimum requirements for key built elements would provide a basic level of accessibility that everyone could expect. Our findings suggest that, at least in the countries included in this study, standards are diverging. There are several possible reasons for this divergence: (a) differences in the research that supports standards development; (b) differences in how the elements of access are defined, both the terminology used and the definitions (or lack thereof) of key variables; (c) differences in wheelchairs used in the various countries; and (d) use of Imperial units in the U.S. that are not always compatible with typical metric dimensions used in the construction industry internationally. Underlying these reasons is the lack of communication between researchers and standards developers at the international level. Without such communication, a consensus on methodologies and approaches will not evolve.

It is important to recognize the need for differences in the accessibility standards from country to country. There are many good reasons for variation, including differences in body size, wheeled mobility technology, economic development levels, and cultural expectations for independence among the population (Rapoport & Watson, 1972). Yet, there is no reason why the benefits of international standardization cannot be achieved while still respecting cultural differences. The research conducted here demonstrates several possibilities: standardize the terms and definitions for the variables of accessibility, establish consensus on how to define accessibility in terms of human performance, and define a minimum level of accessibility that is accepted at an international level. Any country could then exceed the minimum thresholds.

Another important conclusion from this research is very obvious. Research methods have to be improved and documented more thoroughly. In many of the research reports we obtained, there is not enough information to judge the quality of the methods used. Standards of research quality are well known. The reliability of data collection methods needs to be documented across data collection staff and also over time to ensure consistency. The accuracy of new methods should be compared to older methods. The definition of measures has to be precise by using clearly defined landmarks on the human body or equipment. Sample recruitment should be well documented and designed to reduce bias or achieve specific objectives. In general, sample sizes need to be increased for reliable estimates of the distributions of body size and function that are used to inform the standards; however, it is very expensive and difficult, if not impossible, to assemble representative samples. Thus, finding other sampling approaches that can reduce the size of samples needed for reliable estimates is an important priority.

Finally, there is a need to extend this type of research to many more countries. An international standard for the measurement process itself would be valuable. We know of no research on this topic in developing countries where body size, wheeled mobility devices, and environmental conditions are very different than in high-income countries. The rapidly improving development status of Asian and Latin American countries will bring with it increased expectations and demands by their citizens with disabilities. The aging of populations worldwide will also increase the need to support independence for the older portion of the population. In less developed countries, international agencies are supporting massive projects to improve education, health, transportation, and housing. It is important that standards from the Western world are not blindly applied in these societies without determining whether they are appropriate.

ACKNOWLEDGMENTS

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