HANDS-ON ARCHITECTURE

PART I

EXECUTIVE SUMMARY

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PREFACE

This technical assistance document is based on the results and findings of the Hand Anthropometrics Project (Contract No. 300-84-0247), created to develop an information base for designing products that are used in buildings and intended to be manipulated by hand. The study focused on the abilities of people with disabilities affecting hand strength and coordination, a group for which there is a lack of human factors design data.

The citations to volume, part and section in this document refer to the three-volume final report of the project, *Hands-On Architecture*. Volume One, the main research report, summarizes the literature review and presents the conceptual framework for organizing the research and findings. Volume Two presents a method and data for improving design of buildings consistent with hand and arm abilities of persons with disabilities. Volume Three, the basis for this technical assistance document, contains an Executive Summary of the project and a set of recommendations or guidelines that can improve building design.

The complete research report can be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22164; or call (703) 487-4650. Specify order number PB90170861/AS.

HANDS-ON ARCHITECTURE
EXECUTIVE SUMMARY

TABLE OF CONTENTS **PAGE NUMBER**

EXECUTIVE SUMMARY

Purpose

The Hand Anthropometrics Project was created to develop information that can be used as a basis for designing products that are used in buildings and intended to be manipulated by hand. This information base is focused on the abilities of physically disabled people since there is a lack of human factors design data for this group. (Definitions of terms, grip typologies, diagrams, charts, and design implications are contained in Volume 3, Part II.)

Research Activities and Methods

The research activities included:

1. a literature review
2. focus group meetings
3. a building survey
4. laboratory research on human performance issues related to using operable devices and controls.
5. product evaluations in laboratory and field settings

The literature review demonstrated that the successful use of operable devices and controls is heavily dependent on five factors:

1. approach clearances
2. reach limits of the arm
3. anthropometrics of the hand and its grips
4. biomechanic abilities to exert force and form grips
5. psychomotor skills

The literature reviewed covered the fields of general human factors, human factors research on people with disabilities, health sciences research and product design research on accessibility. There have been very few studies on this topic and none of the published studies has developed a conceptual framework to deal with the complexity of the issues. However, there was a great deal of information available in the health sciences and human factors literature on anthropometrics and biomechanics that could be directly applied to the subject.

The review of literature formed the basis for developing a conceptual framework that could help to focus the research, allow the findings to be communicated easily, and be of value in the design process. This framework includes the following elements:

1. a typology of devices

2. a breakdown of task components for using devices

3. a grip typology and definitions (see Vol. 3, Part II, Section 1 for grip typology and grip shapes)

4. a list of attributes of the device

5. a spatial orientation system

This conceptual framework can be used to describe any device in terms of its physical characteristics and method of use.

Three focus group meetings were conducted in Atlanta and Buffalo. They included project staff, disabled consumers and experts in rehabilitation and human factors research. The purpose of these meetings was to obtain first hand ideas from consumers and experts about the major problems faced by people with hand disabilities using buildings. Input was also obtained about the types of buildings that should be included in the building survey and methods of classifying persons with disabilities.

The building survey included on-site surveys of 23 buildings in Atlanta, Georgia, and Buffalo, New York. In each building, the characteristics of all operable devices and controls on the first two floors were documented. Over 250 different devices were studied. Analysis of the data identified the range of differences in design for each device type. For example, the mounting height of door knobs was found to vary only between 39 inches and 41 inches. The results of the building survey were used to determine what design parameters and ranges of values should be explored in the laboratory. The selection of mounting heights, sizes of grip shapes, mounting orientations and other parameters of design were based on the building survey data. The results were also used to select buildings for conducting field research. Since public spaces, where access for research could be obtained, had few products of the kind normally found in residences, it was decided to focus more attention on residential products in the laboratory phase of the product evaluation research.

Over 130 disabled and 20 able-bodied "control" subjects were recruited for the laboratory research. Seventy-three subjects with disabilities were recruited for the field research. Recruitment involved extensive use of print and broadcast media and a qualifying screening interview conducted by telephone. The screening interview obtained data on several demographic variables, cause of disability and three different self report scales of functional ability. From the qualifying pool, 104 disabled and 20 able-bodied subjects participated in the laboratory research. Fifty-two subjects with disabilities and 5 able-bodied subjects participated in the field research. For some research procedures, fewer subjects participated because of attrition in the laboratory sample. All subjects were paid for their involvement. Subjects visited the laboratory 1-3 times for 2-3 hours each visit. The field research was conducted in one 3-hour time block.

The sample used in the laboratory research was diversified in terms of disability type. The major causes of disability were paralysis, arthritis, multiple sclerosis and muscular dystrophy. However, twenty other causes were reported. About 90% of the subjects had disabilities that affected other functions besides hand and arm abilities. The mean age of the sample was 44. All but a few were living in non-institutional living arrangements.

Comparison of data for people who completed all the laboratory research tasks, those that participated in only some procedures, and all those that qualified, showed no evidence suggesting that the complete participation group or partial participation group was any different from the qualifying pool. The profiles of each group on the variables above were remarkably similar.

The laboratory study included three types of research:

1. anthropometrics of reach, hands, and grips;

2. biomechanic abilities; and,

3. psychomotor skills.

In the anthropometrics research, grip size data were obtained by having subjects grasp a tapered cone and wedge. Reaching abilities were determined by fitting trials in which subjects reached for a target. Approach space was measured by recording the amount of clearance subjects needed to operate devices. In addition, reaching and grasping abilities were recorded on videotape. Ten different arcs of reach were recorded for each subject. Thirty-four different gripping positions were recorded. A video digitizing system was used to transfer video frames to digital form and dimensions of reach and grip size were taken off the digitized images using a computer aided design (CAD) system. Baseline data on body stature and arm length were also collected for comparison purposes.

The biomechanics research included measurement of grip strength using a power dynamometer, vigorimeter and pinch gauge. In addition, a Baltimore Therapeutic Equipment Corporation Work Simulator was utilized to simulate the operation of controls and operable hardware. The Work Simulator is a strain gauge attached to an adjustable mount to which various tools can be attached. The machine was operated in "static" mode in which the amount of force applied to a tool is recorded. Tools are attached to a spindle which can be adjusted in orientation or height very rapidly. Custom made attachments were fabricated to create a set of standard grip shapes -- cylinders (bars), discs, spheres and plates in a range of sizes. By using the grip shapes and the inherent flexibility of the machine it was possible to simulate any device found in the field. A set of 24 configurations was selected for testing. All biomechanic testing was conducted with two trials, the results of which were averaged for analysis purposes. The Borg Exertion Scale was used to obtain a subjective rating of effort associated with each trial. The Corlett and Bishop Body Discomfort Scale was also used to ascertain if the research itself had an effect on discomfort.

The psychomotor abilities research included measurement of hand steadiness, manual dexterity and device-oriented speed trials. Hand steadiness was measured with a steadiness tester that records the degree to which a pointer strays from circular targets. Data from this test were used to establish spacing for electronic controls. Comparative data on hand dexterity were obtained by using the Minnesota Rate of Manipulation Test. These data helped to compare the abilities of the experimental sample to those of the general population. Speed trials included measuring the speed in which subjects could push buttons and insert coins and credit cards in slots. Apparatus was constructed in which card and coin slots or buttons could be mounted at a range of heights and at different orientations. Two sizes of coin and card slots and three sizes of buttons were tested at a selected set of heights and orientations. The configurations used in the research were based on the results of the building survey.

The product evaluation research included both laboratory and field studies. In the laboratory, 39 devices were evaluated. In the field, subjects walked through five buildings and tested all operable devices and controls along their path of travel. Forty-two devices were tested in the field. The laboratory and field evaluations were similar. For each trial, research staff recorded what grips the subjects used, to what degree they were able to use the device and how much space they needed to operate it. The subjects evaluated the device with the Borg Exertion Scale and a modification of the Corlett and Bishop Body Discomfort Scale.

Analyses

Data were analyzed in several ways. In general, descriptive statistics were used to describe the anthropometric characteristics of the subjects and their performance on research tasks. Threshold levels were identified for variables for which design criteria could be established directly. These levels were set by identifying what conditions would be necessary to accommodate 90% of the sample. Percentile data were primarily used to establish these threshold values. For example, the recommendations for minimum approach clearances were based on the 90th percentile values for clearances. Each device tested in the laboratory was treated independently. Initially, each device was unique so it was inappropriate to group them until their similarities in use could be identified. Threshold values were established based on the "worst case" concept. For example, if the force exerted during comfortable use on several similar devices differed, the lowest 10th percentile value was used as the "common denominator" for the whole group. Trends in the data were also identified using both measures of central tendency and comparison of percentile rank values. Bivariate statistics were used where appropriate to ascertain the degree of association between variables and the direction of the relationship. Data were presented in tabular form with notations to assist the reader in understanding the source of the conclusions and recommendations.

Findings from the laboratory research were reported at several levels of concern. To establish the generalizability of results, comparisons were made between the experimental sample and the control group and between the control group and, where possible, the general population. A second level was concerned with identifying patterns of interaction between independent variables. A third level focused on identification of threshold levels for design criteria. Finally, additional observations of relevance to design were reported.

Findings from the product evaluation research were reported in several ways. First, specific findings for each device were described. Second, comparisons were made between different devices. Third, specific observations about problems using devices were discussed. Finally, the results of the laboratory product evaluations were compared to the results of the field evaluations.

Results -- Laboratory Research

Anthropometrics

The control group was slightly taller than average and much lighter. The mean arm length and shoulder breadth of both the control and experimental samples were similar to the 50th percentile of the general population. The mean height of the experimental sample was considerably shorter than that of the control group because many were wheelchair users. When generalizing findings of the anthropometrics and biomechanics research, one could expect that the population at large would have similar reaching abilities as the control group and be stronger (due to greater weight); however, the control group may have more endurance (fewer overweight people).

For grip size, the mean performance abilities were similar; but at the lower percentile ranges, abilities were markedly different. A small number of subjects in the experimental sample could not complete the power grip at all. The span grip was easier to complete. A strong relationship was found between the maximum perimeter gripped using the cone and the maximum span grip (see Vol. 3, Part II, Sec. 1.5). These findings have several implications. Wherever possible, grip shapes that do not require the use of the power grip should be selected. The perimeter of a grip shape can be used as a design criterion in place of, or in addition to, grip shape and width. This allows precise evaluations between regular cross sections and more irregular shapes. In terms of grip size only, the diameter for a cylindrical shape used with a power grip should be about 42 mm (1.7 in.) to accommodate people who cannot form small grips easily and those who cannot form large grips.

The video data provided a great deal of information on the anthropometrics of grips. Data on three major design factors were analyzed: cross section (diameter), grip length and grasp space. The results for power grip were compared to recommendations by Diffrient et al. (1981) for the general population. The comparison demonstrated some small differences. The most notable difference was for grip clearance. Diffrient's recommendation for large males was 25.4 mm (1 in.) less than the recommendation derived from this research.

The data derived from the video procedure identified the minimum and maximum cross section (diameters) that can be formed by hand/arm disabled people. However, the selection of the optimal size for any specific application must be determined by other factors as well.

The cone data, for example, identified the cross sections that provide maximum support yet still allow a power grip to be formed with fingers and thumb touching. The cross sections identified from the cone data, therefore, are more useful for designing assists such as handrails and grab bars where both grip strength and support are important. There is more freedom in choice of cross section when strength and graspability are the only important factors such as in the design of handles.

For the power grip, the perimeter of an object can also be an important factor in the design of grip shapes. For example, a handrail could be shaped in an irregular form for which the cross section alone will not insure a complete grasp using an opposing power grip. The maximum perimeter can be established from the wedge data.

The results of the reach fitting trials showed that the reaching abilities of most hand/arm disabled people are well below the abilities of able-bodied individuals. The differences in abilities are much greater for high reach than for low reach. Based on the performance of the 10th percentile of the experimental sample, objects should be located between 864 mm (34 in.) and 1168 mm (46 in.) for comfortable reach without an obstacle. For seated tasks, where people must reach over a counter, cabinet or other obstacle using a side reach, the comfort range should be reduced to between 914 mm (36 in.) and 1041 mm (41 in.). This latter range applies to objects that are within 305 mm (12 in.) from the obstacle's leading edge. Only disabled people with reaching ability levels in the top 10% are able to reach heights that the average able-bodied individuals can attain easily. This comparison points out the importance of reach limits for designing and locating devices. In many cases, inability to reach a device is a greater limitation than inability to manipulate the device itself.

The video reach results can be compared to the results of other procedures in the project involving reaching abilities. The heights identified for comfortable free reach at the 10th percentile are considerably below the abilities of the sample when measured through other means. The horizontal reach results are consistent with the reach distance data. Since the free reach data do not reflect the ability of the entire sample and the other measures of reach ability are more directly related to actual use of objects, more confidence should be given to the data from the latter methods.

There are three kinds of approach clearances that have an effect on the accessibility of devices:

1. side displacement -- clear distance to either side of the device;

2. reach distance -- reaching range measured in a direct line from the device to the user;

3. front displacement -- space clearance directly in front of the device perpendicular to the mounting plane.

Data for determining requirements for these clearances were obtained from the shoulder location information collected during fitting trials, biomechanic tasks and psychomotor tasks. For biomechanic tasks, side displacements of 333 mm (13.1 in.) to 485 mm (19.1 in.) were needed. For the psychomotor tasks, the space required was only 208 mm (8.2 in.) to 361 mm (14.2 in.). Since side clearance is necessary at both sides of any device in order to accommodate both left-handed and right-handed people, the width of a front approach area is double the value for side displacement. The difference between these two sets of findings is due to the difference in the nature of the tasks. Both sets of tasks required reaching to several different heights. In the biomechanic research, the subjects were attempting to exert force on objects using a variety of different grips and motions. In the psychomotor tasks, they had to insert objects in holes or press buttons with only slight resistance; variation between the grips or motions used was slight. The biomechanic trials *elicited much more repositioning* to obtain *greater mechanical advantage* close to the device. In addition, the psychomotor trials were tasks for which vision was critical for good performance. Thus, subjects tended to stand further back from the device and more toward its centerline where they could see the device easier; the result was a reduced side displacement. Existing code requirements of 762 mm (30 in.) for front approaches appear to be satisfactory.

Two values are important for establishing reach distance. The first is the close-reach distance used to operate a device; some people have to get close to a device to use it conveniently. The second is the far-reach distance; some people will find it more convenient to stand at a distance from the device. For biomechanic trials, a close-reach distance of about 198 mm (7.8 in.) and far-reach distance of about 787 mm (31 in.) would accommodate almost all the experimental subjects. For psychomotor tasks, it was found that a larger close-reach distance, 295 mm (11.6 in.), could be used. This is consistent with the need to stand further back from a device when the task has a major visual component. These values can be accommodated within the depth of front approach clearances now found in most codes.

Biomechanics

The results of three out of the four basic grip strength tests demonstrated that the experimental sample had much lower grip strength than both the control group and average values for the population at large. The difference in performance between the experimental and control subjects was much greater for the power grip strength measured with the dynamometer than with the vigorimeter. This confirmed our belief that the power dynamometer has limited usefulness for measuring the grip strength of hand disabled people. On the other hand, the one measure of grip strength on which differences between the two groups were not evident was the pinch strength measured with the small bulb of the vigorimeter. The bulb had a limited range at the high end of the scale; thus it was not sensitive enough to register the highest values for the control group. The data for the two other tests both demonstrated that the disabled group had, on the average, only half the grip strength of the able-bodied group.

The ability to apply forces to standard shapes was influenced by several interrelated factors:

1. orientation of the object;
2. direction of the force exerted;
3. size of the object;
4. operating height; and
5. shape of the object.

Based on the findings, and because of their interactive nature, no universal recommendations could be made for optimum values for any one of these variables. Mean forces for the experimental group were about one half those of the control group for most devices tested. The degree of force that could be exerted appears to be a function of at least two or more of the factors.

The strongest impact on ability was related to shape. The experimental and control samples both were able to achieve the highest forces with bars used with linear motions. Next came the small plate, operated in the up-down direction. The worst shape was a small plate pulled toward the body. All other shapes were similar in performance.

There were two differences in exerted forces that were solely related to orientation. Subjects applied greater forces to cranks operated in the sagittal plane than in the transverse plane. They applied greater forces to vertical bars than to horizontal bars.

Depending upon the orientation and shape of a device, either pulling or pushing could be easier. Bar shapes (cylindrical) used in an orientation similar to handrails, for example, were easier to push than to pull, whereas bars used in a vertical orientation were easier to pull than to push. For the control sample, the differences in exerted forces related to direction were not as great.

Size was both negatively and positively related to level of force exerted, depending on the shape. For the bars and the spheres, the relationship was negative -- small sizes produced more force. For the disc shapes, however, the relationship was reversed.

Operable height had the least relationship with amount of force exerted. In fact, there was practically no variation for the control sample with respect to this factor. One surprising finding for the experimental sample was that greater forces could be exerted on plates used as toggles in the up direction than in the down direction when the plates were mounted at the highest position. The reverse was found at the lower positions.

Thus the applied force data demonstrated that broad generalizations, such as "pushing is easier" cannot be made. The data does provide, however, a basis for developing design guidelines that take into account the interactive nature of the factors involved. The following qualitative recommendations can be made with respect to design for application of force:

1. devices can generally be located at any height within the range of comfortable reach without affecting exerted force;

2. for maximum force, a bar shape should be used with a linear motion;

3. knobs and other shapes used with a disc grip should be as large as possible within the range of comfortable grip;

4. spheres and bars used with a power grip should be as small as possible within the range of comfortable grip particularly if used for pulling;

5. small plates should not be used for pulling toward the body unless the amount of force required is essentially zero;

6. bars in the horizontal orientation are better for pushing and bars in the vertical orientation are better for pulling;

7. rotation is not desirable with any shape except bars used as levers;

8. cranks should be operated through the sagittal plane rather than the transverse plane;

The research procedures allowed subjects to use any grip they desired to apply forces to the standard shapes. Although the differences in grips used were not studied *per se*, it was possible to identify the most effective grips based on the pattern of results. Power or push grips, as used to push and pull bars, were most effective. Power or hook grips used to pull bars were next. Pinch or flat hand grips used to pull small plates down were third. Disk, span, finger push and pinch grips used in other directions were last.

From the data, it was possible to derive a set of force limits for different combinations of shape, direction of motion and orientation that would accommodate different percentile ranks of the sample (see Table 1).

The general similarity of trends in the data for both the control and experimental group lend weight to the validity of the findings.

Psychomotor Abilities

Generally, the experimental sample had much less manual dexterity, speed and coordination than the control sample. The results of the general tests of psychomotor abilities were reflected in the mean times for using slots and buttons: the experimental group was, on the average, 74% slower for slots and 54% slower for buttons.

Card slots were easier to use than coin slots. The wider slots increased speed substantially but, in absolute terms, the difference is minor, amounting to only a few tenths of a second. The larger buttons were easier to use, particularly for the experimental subjects with the lowest level of ability. The largest buttons required times that were considerably smaller than the smallest buttons -- up to 30% reductions were found. Height, orientation and size of slot were interrelated.

The findings show that the use of slots is a task for which visibility is critical. It is important for buttons also, but not to the same degree. Design factors related to visibility include lighting, height, size of device and orientation of the device. The importance of visibility was emphasized by the findings on height and orientation. The higher slots and buttons were easier to use. Higher position brings the device in a more favorable location within the user's field of view. For the slots mounted on a vertical plane, vertical slots were generally easier to use than horizontal slots. In the vertical orientation the slot width is not foreshortened so it is easier to see. In a horizontal plane, those slots positioned parallel with the user's body were easier to use than those positioned normal to the body. In this plane, both orientations are easy to see; thus the advantage goes to parallel slot because it can be used without deviation of the wrist.

The performance of the control group for the steadiness test was much better than the experimental group. Data on percent of deviance for each target for the sample as a whole (mean values) and for the 10th, 50th and 75th percentiles were computed. These data were used to establish a tolerance for unsteadiness. Adding this tolerance to one half the finger width of a 50th percentile adult male yielded minimum space dimensions. For the mean values, the performance of the experimental group indicates that spacing of buttons as measured from the center of the button to the edge of the next button should be at least 18 mm (0.7 in.).

Product Evaluation

The devices in the laboratory were, on the whole, not difficult for the experimental sample to use. For more than half of the devices, however, there was a small group of individuals (10 - 15% of the sample) who could not complete operation of the device. The devices that were problematic generally required the use of pinch or disc grips. There were *several other devices that required awkward or unusual hand movements.*

Subjects were familiar with most of the products; few of the "unfamiliar" devices were difficult for them to use. Therefore, data do not indicate that inability to use a device was due to lack of experience with it.

Subjects utilized many different grip types and most products were used with more than one grip. Many alternatives to the standard hand grips were used, including the back of the hand, knuckles and fist. The most awkward alternatives used were two hands or fists in place of a pinch grip or disc grip. Even the simplest of all grips, the flat hand push, was not possible for many people who could not flatten their hands. **Products are more usable if several alternative modes of operation can be accommodated.**

Two hands were used very infrequently. For a small proportion of the trials, subjects' *initial grips evolved into secondary grips. This happened more often with locks and* cabinet/drawer pulls than anything else. The data on the use of two hands and secondary grips suggest that using door hardware may be a more complex task than other products because of the presence of both locks and door openers.

A large number of the products tested were uncomfortable for more than 25% of the sample. Although many of the products that caused discomfort required relatively high forces to operate, there were others that did not. This group included products such as a wedge shaped drawer pull that had to be grasped with a pinch grip, a shower head that had sharp protrusions, and locks requiring pinch grips. Although the keyed lock required a pinch grip, it had a low force of operation and was not rated as poorly as the others in terms of discomfort. Twisting, or deviating the wrist, and the need for form a pinch grip apparently caused discomfort for many people. Thus, the need to exert large forces in an absolute sense did not necessarily cause discomfort as long as a grip suitable for applying large forces could be used.

Levels of self-rated exertion were not very high, which is consistent with the type of tasks involved in the research. Exertion ratings were only weakly associated with time of operation. The devices requiring larger forces, however, had higher mean exertion ratings. *These findings indicate that duration of effort is not as critical as maximum force required* for the tasks studied.

Products that were rated as having a high relative exertion level were also rated as having a high relative discomfort level. Those that were worse in terms of general performance were also worse in terms of discomfort. However, the evidence for an association between exertion ratings and general performance was equivocal. There can be many reasons for not being able to use a device. The lack of a strong association here indicates that force of operation is not the most important factor in itself.

The findings on product evaluations lead to the following general principles for design of products.

1. grip shapes should allow the use of several grips and alternatives to standard grips;

2. with the exception of lever handles, rotational movements in combination with pinch or disc grips should be limited to small maximum forces;

3. the grip shape should be free from sharp edges and accommodate finger sizes;

4. door openers and locks should be simplified as much as possible to reduce the need for use of two hands and secondary grips;

5. all devices should be usable without reliance on a pinch grip or disc grip.

General Observations

Some general observations can be made on the results. A theme evident in many of the findings is that the performance range of the disabled people as a group overlapped that of the control group. Many of the disabled people performed at the same level as a sizeable portion of the control sample. Being disabled in one functional area does not imply total disability. In our research, no distinction was made between hand or arm disability. Some subjects who had hand disabilities had no problems reaching, and vice versa. Because of such specific variation in functional ability, recommendations should not be based on mean performance if other alternatives are available.

Recommendations should be based on the lowest "common denominator" -- the people who have the most difficulty. This group is more likely to consist largely of wheelchair users. Although many wheelchair users performed above the median for the experimental sample in the laboratory research, it is a fallacy to assume that satisfying some wheelchair users will always satisfy the most severely disabled group.

A comparison of findings from the fitting trials and actual device trials demonstrates some conflicting findings. The 10th percentile level in the fitting trials (no obstacle) for the experimental sample was 1168 mm (46 in.). However, all but five subjects could use coin slots at 1219 mm (58 in.) high. Moreover, all but five could use buttons at 1372 mm (54 in.). Five subjects comprise less than 5% of the sample. Five subjects reached higher to insert coins in slots and to press buttons than they did to touch a quarter to a target in the fitting trials. It was easier to touch coins to targets than to insert coins in slots. However, it was easier to press buttons than to touch a quarter to a target (no grasping was required and a quick "slapping" motion sometimes was used by subjects). Other than the purpose of the reach, the procedure used for the slots and buttons was identical to that used for the fitting trials except that the slots and buttons were not adjusted to "comfortable" reach. Thus, it appears that, given conditions where grasping is not necessary, reach to 1372 mm (54 in.) is possible for all but a few individuals. Where grasping is necessary, only a few people cannot reach to 1219 mm (48 in.). The difference between using slots and the fitting trials must be attributed to the greater motivational component and the elimination of adjustments in the former task. **In general, 1220 mm (48 in.) can be used as an upper reach limit.**

Results -- Field Research

In general, the overall performance of the subjects on all of the devices tested was good. Of the 1716 attempts at task performance, 1477 (86%) were successful and only 239 (13.9%) were unsuccessful. However, only half (21 out of the 43) of the devices were used at an acceptable rate of 90% or more.

Subjects used their hands primarily to complete the tasks. In fact, of the 1477 successful performances, 90.4% were completed by the subjects using only their hands. An additional 6.1% used their hands but were aided by either a wheelchair or some other part of their body (i.e., their hips pushing open a door) and only 3.2% of the tasks had to be accomplished by using some means other than one's hands. Although the 3.2% is a small percentage, the majority of those using an alternate method to completely operate a device were wheelchair users who used their chairs (67.3% of the time) to push open doors.

The most significant factor affecting performance was standing or seated posture (in a wheelchair). When the 1716 attempts were divided into standing vs. sitting, 96.1% of those who were standing were able to operate the devices successfully whereas only 81.8% of those in wheelchairs were able to do so. Moreover, whereas subjects who were standing were able to operate 36 of the 42 devices 90% or more of the time, only 12 devices (5 were elevator buttons) could be considered as usable (above 90% success rate) by persons in wheelchairs.

Eighty percent of the subjects were able to operate the devices using only a primary grip. Secondary grips and the use of other body parts to aid in the operation of devices were used for those devices which caused the most difficulty. Specifically, the 10 doors with self-closers accounted for 61% of all of the devices which required more than a primary grip. Although there were 5 categories of devices defined in the Building Survey (electronic controls, handles, receptacles, dispensers and assists), only 4 of these categories were included in the testing. There were not enough ambulatory subjects to test handrails or other assists.

Electronic controls included buttons on telephones, elevators, a water fountain and a stamp machine. Performance on all of these devices (except two, where 17 of 19 people could not reach) was well over 90%. Thus, it appears that controls themselves, when located where they can be reached, do not pose a great problem for persons with hand impairments.

Handles were represented by a range of different devices including toilet flush handles, water fountain handles, door handles, telephone receivers and sink faucet handles. The data demonstrated that the problems with use of these devices were due to factors such as mounting height, obstructions to use, the amount of force required or the type of motion required to use a device. In general, those devices which were operated primarily by the hand alone resulted in a higher rate of successful performance than those which required subjects to use alternate methods for either partial or complete operation. For example, faucet and water fountain handles were operated almost exclusively by hand (92% or more of the time) and had success rates ranging from 85 - 95%. On the other hand, entry/exit doors required much greater force to operate; subjects therefore used other parts of their anatomy to aid in the operation of these products. In fact, the 7 entry doors accounted for 58% of the number of instances that subjects used some other means to aid in performing a task. None of the doors had an acceptable rate of success.

Exterior entry doors had, as a group, the worst success rates of any of the products tested. Two of these doors required 7.3 kg-*f* (16 pounds) of force, while another required 5.4 kg-*f* (12 pounds) to pull open. This task was particularly difficult for a wheelchair user. As a consequence, the success rates for this group of doors ranged only between 67% and 74%.

Interior doors pulled open as did exterior entry doors but, unlike the latter group, had much lower opening forces. None of those tested required more than 3.6 kg-*f* (8 pounds) of force to open. As a consequence, the performance rates were far higher on these doors than on the entry doors, ranging from 90% to 97.6%.

The round knob was one of the few products where the inability to perform a task could be directly linked to a grip related problem. Although the door on which the knob was located was identical to the two other interior doors tested in the same building, one of the latter had a pull handle and the other had a lever handle. Every other interior door tested had pull handles. Unlike the handles which could be operated by any number of variations on the power or hook grip, the knob could be operated only by a disc grip.

There were problems with toilets related to mounting height and the design of the environment in which they were located. First, the mounting height of the handles varied from very low 622 mm (24.5 in.) and 699 mm (27.5 in.) in two buildings to 1041 mm (41 in.) in another. Second, one stall was only 914 mm (3 feet) wide, whereas the other two were 1524 mm (5 feet) in width. These factors are extremely important because, although none of the ambulatory subjects failed to operate these devices, wheelchair users failed 25 times. In addition, 22 out of the 25 failures on the 3 toilets were the result of wheelchair users not being able to reach the handle. One-half of those failures occurred in the narrow toilet stall alone, where wheelchair users were forced to reach across the toilet from the front in order to operate the handle. At the other two sites subjects could pull alongside the flush handle and simply reach over to use it. However, because these two handles were so low, the failures in these cases resulted from subjects who could not lean over to operate the handle without falling out of their wheelchairs.

One type of product with handles demonstrated additional problems unrelated to the design of the handle itself or its surrounding environment. Each of the three water fountains tested had a different type of operating mechanism. The success rates for the use of controls were very high and varied only slightly (from 95% to 100%). However, despite the apparent ease in operating the controls, very few of the non-ambulatory subjects could actually drink from the fountain. This was a result of their inability either to reach the stream of water or to prevent water from spilling all over them. Therefore, despite the appropriateness of the hand controlled mechanism, the overall design of the fountain and its location created serious problems of usability.

Receptacles tested included coin slots, card slots, key slots and mail slots. Within this group there was great disparity in the success rates of the five slots tested, ranging from a low of 53.7% (which was the second lowest rate for all devices) to a high of 97.6%. Mounting height played an important role in successful use of these devices.

The mail slot, which was far larger than the object inserted into it, had a very high success rate of almost 95%. Because the slot was a large target, many people were able to flick the envelope into the slot without having to reach to the 1194 mm (47 in.) height at which the slot was located. As a result, only two wheelchair users were unable to complete the task.

The key slot proved to be troublesome for both the standing (83.3% success) and seated (73.1%) groups. However, this was not necessarily related to an inability to put the key in the slot. Rather, it was the inability to work the lock mechanism. Either the key was difficult to turn or subjects turned and waited for the lock to click open. Because subjects did not know that they had to turn and pull at the same time, they often kept turning without being able to open the door.

Dispensers included the coin return on the telephone, the fare card return and the stamp removal slot on the stamp machine. Only one of these devices was easy to use. Both the stamp and fare card machines partially ejected objects which then had to be gripped and pulled out completely. Both were operated primarily by pinch-type grips (97% on the fare card and 96% on the stamp). However, the fare card, which is the size of a credit card, stuck almost completely out of the machine and therefore had a fairly large surface (about 76 mm or 3 in.) to grip. The stamp on the other hand, barely (about 13 mm or 1/2 in.) protruded from the machine and, even users without hand impairments had a hard time getting the stamp out without ripping it. As a consequence, the fare card had a 95% success rate compared to the 53.3% rate (the lowest of all of the devices) for the stamp machine. The coin return required several different steps and grips (e.g., insert finger, locate coin, trap coin, slide it out and pinch it) to secure the coin. Thus performance on this device was poor.

Although environmental measures (light and noise levels, temperature, etc.) were gathered at the test sites, there was little, if any, variation in these factors during the course of the project. As a consequence, these conditions probably had little influence on the subjects' abilities to perform the tasks. **The results of the field study suggest that three of the major determinants of successful operation of hand operated devices are: 1) approach clearance, 2) mounting height and 3) operating force**. All three have great impact on non-ambulatory individuals.

Task performance is affected by the reach distance to a device. This is a primary problem for wheelchair users whose approach is often restricted by obstructions in the approach area. An even more significant factor affecting task performance is mounting height. In this study, mounting heights ranged from 522 to 1549 mm (24.5 to 61 in.) from the floor. Within this range, subjects in wheelchairs had the most difficulty reaching devices mounted over 1321 mm (52 in.) and under 825 mm (32.5 in.). Devices which are easily used at heights within the comfort range (e.g., elevator controls) become more difficult to use at extreme heights. The performance data indicate that the 46 out of 53 subjects who failed to operate those devices over 1321 mm (52 in.) in height, failed to do so because they could not reach the device. Similarly, 14 out of 17 subjects who failed to operate the two low flush handles also failed because they could not reach the device. In contrast, for all of the other devices tested, only 2 out of 169 failures were attributable to the subject's inability to reach the device. Thus, it appears that those devices which are unobstructed and which are mounted within a range of 826 to 1245 mm (32.5 to 49 in.) from the floor (to the midpoint of the device) at least provide the opportunity to be operated. Those that fall outside this range are either too high or too low and are apt not to be reached by wheelchair users. As a consequence, the design of the device would make little difference.

The third key factor is the amount of force required to operate a device. This is particularly relevant to devices which required finger-thumb opposition grips such as power or hook grips. These devices required, on the average, more power (mean force of 3.8 kg-ƒ/8.3 pounds) to operate than any of the other categories (mean forces ranged from 0 to 2.7 kg-ƒ/6 pounds) and accounted for 38% (63) of the 167 failures not attributable to reach. As a result, there is a high negative correlation (r = -50) between force and successful use. The greater the amount of force required to operate a device, the lower the rate of successful performance will be.

Although approach clearance, mounting height and operating force individually affect performance, the three factors acting together may account for the low success rates of the wheelchair users. Even though most of the devices were within the acceptable ranges of heights and force, wheelchair users, nonetheless, were able to operate only 10 devices at a minimally acceptable success rate of 90%. This can be explained, in part, by the fact that wheelchair users are forced to grip and operate devices (which were designed to be used while standing) from a sitting position. The combination of large reach distance and low shoulder and elbow position reduces the mechanical advantage that would otherwise be obtained in a standing position. Thus wheelchair users also have difficulty operating devices that require moderate (but still reasonable) levels of force and are located within the comfort range of reach. Two faucet handles, for example, which required 2.7 kg-ƒ (6 pounds) of force to operate had success rates less than 90%, whereas the handle which required only 0.9 kg-ƒ (2 pounds) had a success rate over 95%.

In summary, **the field research demonstrated that there are a number of factors which affect the use of devices: those which are related to the design of the device, the design of the equipment on which the device is located, and the design of the environment in which the equipment is found.**

Specifically, the data indicate that, regardless of an individual's hand impairment, posture (whether someone is in a wheelchair or standing) is the most important factor in task performance. Ninety-six percent of the time subjects who were standing were able to perform the task successfully. Subjects in wheelchairs were successful only 82% of the time. Moreover, the three key factors related to posture appear to be approach clearance, mounting heights and operating force. Whereas persons with hand impairments generally have little difficulty using buttons, they also have little difficulty with levers, pulls, and even slots, when the devices are located between 825 and 1214 mm (32.5 and 48 in.) from the floor and when the equipment does not require more than 5.4 kg-ƒ (12 pounds) of force to operate. In addition, **the approach area must be level to the operating position (especially at doorways) and free from obstructions in order for non-ambulatory people to effectively use the device.**

Nonetheless, despite the context-related problems, there are some conclusions to be drawn about the devices themselves. First, although performance rates on certain slots were low because subjects could not reach them, many subjects who were able to insert the coins (or key) had great difficulty in doing so. Slots would be much easier to use if they required less precision. The coin slot on the fare machine, in addition to being lower than the other slots tested, also required less precision since it was located on a horizontal surface which acted as a "catcher" for the coins. This design required less precision on the part of the user.

Second, with the exception of the round door knob which could be gripped firmly only in one place and in one way, subjects could operate door openers many ways and in various places. As a result, despite problems with the weight of the doors, most subjects were able to grip the handles.

Third, dispensers are effective only when the object they dispense protrudes far enough to be gripped. While there is not enough data to make a recommendation on this issue, the 13 mm (1/2 inch) that a postage stamp protrudes from a stamp machine is clearly not far enough. However, the 76 mm (3 in.) that the fare card protrudes may be more than is necessary. While other data are needed to determine the optimum grip area, it is apparent that the farther the object protrudes, the greater the amount of flexibility an individual will have in gripping it successfully.

Finally, the amount a device protrudes from the mounting surface plays a role in ease of operation. Although a set of elevator buttons that protruded from the panel did not have higher success rate than other elevator buttons that did not protrude, subjects reported that they felt the set that protruded was easier to use. This occurred because the protruding buttons were easier to hit with any part of the hand or other body part despite the fact that they required twice the force of some of the other buttons.

Thus field study demonstrated that, context notwithstanding, the most effective devices are those which are most flexible and most forgiving. They are devices which offer the opportunity for an individual to use them in a number of different ways.

Comparison of Laboratory to Field Research

The field research was able to study variables that were not present in the laboratory work. The naturalistic study provided the opportunity to observe people in a non-structured situation using products on an everyday basis. Unfortunately however, there were few disabled people observed under these conditions because their presence in buildings other than institutions is not concentrated enough. Many disabilities of the hand are not immediately apparent to a detached observer, so it is difficult to asses accurately the number of affected persons in other than a controlled situation. Although the naturalistic research observations did not identify any instance in which users could not operate a device, nine products were found to cause a significant level of difficulty.

In the laboratory, only door openers and simulations of openers were tested. In the field, it was possible to observe the complete use of doorways. Six of the nine devices were doors: for five of these doors, over 30% (and in one case, almost 50%) of the users were observed having difficulty using the door. The two main problems were the speed at which the door closed and the opening force required. The disabled sample also had problems with the same devices. The general population, then, is not immune to difficulties using devices, even though these difficulties may not pose a strong barrier to use of a building.

The controlled testing in the field used methods that were practically identical to those used in the laboratory product testing. There were some significant differences in the sample of subjects, in that the field research sample was much smaller than the laboratory research sample. Although the causes of disabilities exhibited by this sample were quite diverse, the frequencies for the various causes were considerably different. About one third of the laboratory sample reported having arthritis while less than 10% of the field research sample reported having this condition. There was also a larger portion of subjects in the laboratory sample who reported having quadriplegia and paraplegia than those in the field research sample. A much larger proportion of people in the field sample reported having cerebral palsy. There was also a larger number of subjects with multiple sclerosis and muscular dystrophy. Finally the field research had a large proportion of subjects who used wheelchairs.

Comparing anthropometric data on the two samples shows that the field research sample had a higher mean weight, wider shoulder breadth and longer arm length. Thus, they were generally larger and could be expected to have better reaching abilities, provided that their reaching abilities were not more limited due to disability.

In general, the field research sample was just as diverse in its makeup as the laboratory sample. However, it is likely that the performance of the field sample would be worse for reaching tasks because of the increased proportion of wheelchair users. One could also expect that the field research group would suffer less pain and discomfort on the whole because there was a smaller proportion of subjects with arthritis. On the other hand, they would have lower levels of strength available over all because there was a larger proportion of people with cerebral palsy, multiple sclerosis and muscular dystrophy. Thus, the differences may cancel each other out.

The results of the field research can be compared to those of the laboratory research in two ways. First, actual performance on the specific devices can be compared to predicted performance based on the recommendations of the basic human performance research done in the laboratory. Second, performance on similar products and types of products can be compared between the laboratory product testing and the field testing.

Table 2 lists all the devices tested in the field. Each device was evaluated against recommendations for three variables:

1. approach space

2. reach limits

3. force limits for the shape/orientation/motion configuration

Grip shape and grip clearance are not included since the field research found that for the devices tested unsuccessful performance could be attributed to the design of the device for only 8% of the trials.

The table includes notations with respect to whether or not the device met the recommendations. Based on that evaluation, the success of the recommendations in correctly predicting the usability level of the device was noted. The actual success rate of the sample is included in the table as well.

The results of this analysis demonstrate that for 34 of the 42 items, the prediction was successful. For two of the devices, a prediction could not be made because of lack of data. The two variables that demonstrated the least compliance with the recommendations were force and reach limits. Almost all the devices had adequate access space. A review of the table indicates that for the 33 products for which force was a relevant variable, only 14 met the recommendations. Only seven products did not meet the recommendations. There was not one device that failed both the reach and force recommendations. Most devices that require force to operate were located within the most comfortable part of the "normal" reach range.

Two possibilities exist for predictions not being accurate: a product may not meet recommended design criteria yet be easy to use, or a product may meet the criteria and be difficult to use. All the six inaccurate predictions were in the first category. Moreover, all but one exceeded force recommendations. The force required to operate these five devices was always above the 10th percentile performance level (yet below the 25th percentile level). Four out of the five devices were lever handles on water fountains or door pulls requiring a hook grip. The fifth was an elevator button that exceeded by a slight amount the recommended force for small push plates. The sixth device for which the prediction was inaccurate was an elevator button that was located well above the high limit of the recommended reach range but that required only an insignificant amount of force to activate.

These findings suggest that either performance on these types of devices of some subjects in the laboratory may have been abnormally low or the field research sample may have had slightly better abilities. The latter can be discounted because of the generally successful prediction rate. Thus, the maximum force limit recommendations derived from the laboratory research could be increased slightly for small push plates, vertical pull bars and horizontal levers used in the down direction. Using the 25th percentile performance levels for these particular shape/orientation/motion configurations would be appropriate. An across-the-board shift to higher values, however, is not warranted since there were several other appropriate devices.

There is only one possible explanation for the sixth inaccurate prediction. Since the force of activation was so low, wheelchair users with limited reach could "slap" the high button with an inaccurate motion. This type of motion was used frequently in the laboratory research with buttons. There were six other devices in the field research that were mounted above the recommended heights but were not usable. All of these required either precision movements to use or the user had to grasp and hold an object while accomplishing the task; 90% of the sample could not operate any of these successfully. In the laboratory research, few subjects had problems with buttons mounted at 1372 mm (54 in.) but the buttons used required virtually no force to operate and were individually mounted so that accuracy was not critical. The recommendations from the laboratory research on reach limits were based upon the fitting trials and free reach trials, where comfort was the criterion because the study of applied forces identified the importance of the relationship between reach and force. Devices that have to be grasped and manipulated are easier to operate at lower heights.

In light of the field research finding for the high elevator button and the laboratory research with buttons, the recommendations for reach limits should be adjusted to allow buttons requiring less than the maximum allowable force, mounted individually, to be higher than others on a side reach approach. Thirteen hundred and seventy-two mm (1372 mm or 54 in.) would be appropriate in such cases.

A similar analysis was made between the initial recommendations from the basic laboratory research and the results of the laboratory research and the results of the laboratory product testing. Unlike the comparison above, there was a wide divergence between the recommendations and the testing results. For over 50% of the products, predictions were wrong. In general, it was the operating force recommendations that were inaccurate predictors of performance. Evidently, when confronted with a real objective and purpose, the subjects' definition of "comfortable" changed.

The difference in successful prediction between the field testing and the laboratory product testing can best be explained by the method of testing. All the products in the laboratory were mounted in convenient positions and the total testing period was much shorter than in the field. Subjects may have been willing to expend greater amounts of energy in using each product and thus, their success rate was higher than what would be expected from the basic testing.

It is clear from both field and laboratory product evaluations that performance on actual devices can exceed performance in abstracted tasks. The laboratory product evaluations confirmed the need to shift initial operating force recommendations to a level higher than the 10th percentile and extend this shift to the full range of grip types. A few other necessary adjustments to the recommendations were also discovered.

Recommendations for Design

The findings of the research translate into recommendations in two forms. The first is a set of recommendations for enforceable standards that could be adopted by standard-setting and code enforcing authorities. The recommendations are generally presented in the form of minimal thresholds and include a rationale for the performance levels proposed as well as a qualitative assessment of cost impact. The second is a guide for architects, product designers, design reviewers and specifiers. The guide helps the user to consider all the relevant aspects of human performance and to make decisions according to the level of accommodation to the population they wish to achieve.

The following is a summary of the recommendations for design requirements that could lead to revisions of and additions to accessibility standards (original measurements were made in metric and converted to English units):

1. The required clearance for a side approach should be changed to set the side of the clearance back 6 inches (152 mm) from the device.

Rationale: Front displacement data for side reach demonstrate that wheelchair users position themselves back from the device so that they can see it.

2. The maximum height of an operable part of any device should be 48 inches (1220 mm) with the exception of side reach to devices requiring very little force to operate with a side reach.

Rationale: Reach limits are one of the most important factors in determining successful use of a device; mounting heights above 48 inches (1220 mm) were impossible to overcome by more than 10% of the research sample. Only devices with very low force requirements were operable.

3. Limits for the maximum forces allowable for the use of devices should be changed from the current 5 lb (2.2 kg-*f*) to reflect the effects of grip shapes, orientations of devices and movement directions (see Table 1).

Rationale: The research results indicate significant differences based on these factors. Using the "low" figures in the table would accommodate all but the bottom 10% of the research sample.

4. For each of seven standard grip shapes, size and clearance dimensions should be established based on anthropometric data to augment the current requirements for grab bars and railings.

Rationale: These data were previously unavailable.

5. The diameter of railings and grab bars should be folded into the requirements proposed in No. 3 above and revised to allow diameters of 1.3 inches (33 mm) to 1.7 inches (43 mm).

Rationale: This was the range of abilities to form a power grip as found in the research. The optimum size for gripping would be the 50th percentile value which was 1.7 inches (43 mm).

6. There should be a clearance specified for the minimum spacing of push buttons -- 0.7 inches (18 mm) -- from the edge of a control to the edge of the next control.

Rationale: This would accommodate the abilities of all but 10 percent of the research sample; the proposal is 0.2 inches (5 mm) larger than the spacing on the current AT&T public telephone keypad.

7. There should be requirements added to ensure that clearance is provided at dispensers for a disabled person to grasp the object to be removed.

Rationale: Previously, no data were available on this topic.

8. A requirement for the minimum dimension of coin and card slots should be added -- 0.12 inches (3 mm) wide.

Rationale: This was the smallest width tested in the present study that proved workable. There are no data available to indicate that smaller widths would be usable.

9. The force to operate a keyed lock should be no more than 4 lb (1.8 kg-*f*).

Rationale: Only ten percent of the subjects could not use keyed locks. This was the 25th percentile value for rotating plates with a pinch grip.

10. A limit should be included for the maximum allowable force for pushing open a receptacle door -- 8 lb (3.6 kg-*f*).

Rationale: Data on this variable were previously not available. This value is the 25th percentile level.

11. The requirements for the operation of controls and equipment should be revised to limit handles to those that can be operated with a fist, a hook, flat hand or finger push grip.

Rationale: These are the grip types that are most "forgiving" -- they are easiest for hand disabled people to use. Devices usable by these also allow alternate grips most readily.

12. The requirement for structural strength of grab bars should be revised to accommodate a maximum load of 270 lb (120 kg-*f*).

Rationale: This was the maximum weight recorded from the sample; it exceeds the design load in the *Minimum Guidelines and Requirements for Accessible Design*.

13. Standards should include a requirement for the maximum force required to pull or push open a door -- 8 lb (3.6 kg-*f*) seems satisfactory, but there were no doors tested that had forces between 8 lb (3.6 kg-*f*) and 12 lb (5.4 kg-*f*).

Rationale: Door opening forces higher than 12 lb (5.4 kg-*f*) could not be managed by about 30% of the field research sample.

Design Implications

The recommendations for enforceable standards have significant implications for the design of several commonly used and specified products found in buildings. To illustrate these implications, the applicable design criteria for some specific products are summarized in Volume 3, Part II, Section 4.0.

Future Research Needs

The research undertaken in this project was the first comprehensive examination of human performance of people with hand/arm disabilities. As such, the results cannot be considered complete or definitive. Replications of this work should be made and additional issues should be studied. Moreover, there are some findings that suggest the need to develop different research methods, or at least, to modify those described here.

The main research need is to examine the impact of modifying factors on the basic performance data. The field research completed in this project was limited to one geographic region and one season (summer). The impact of cold temperatures on the use of devices outdoors was not examined. In addition, the field research was completed only during daylight hours; therefore, the impact of low light levels was not studied. The laboratory research indicated that psychomotor tasks have a large vision component; it is likely that low light levels would have a great impact on task performance with certain kinds of devices.

The impact of different settings on performance is another modifying factor that should be investigated. The field research was conducted in many different building types primarily to insure the inclusion of a wide variety of products. However, the social context of the buildings could not be investigated. Research should be implemented that studies the impact of time pressures associated with congested buildings (i.g., transit stations during rush hour, cafeteria lines, etc.). Under these conditions, it could be expected that small differences in the speed of performance, as found in the laboratory, might become significant. There is a major problem with studying such conditions in the field in that, as the naturalistic research demonstrated, the use of products in buildings by people with disabilities, or, for that matter, able-bodied people, is not frequent enough to allow cost effective data collection using simple observation. The simulation of crowded conditions and time pressures in a field setting might be a good way to overcome this problem. A large group of people could be enlisted to create congestion while research subjects use the products being studied. Another method would be time lapse photography.

Another aspect of environment as a modifying factor is the study of products in private places -- work settings and residences in particular. Such research might best be conducted through an interview method or building walk-through combined with user interviews.

In this project, reaching abilities were studied in the laboratory in three different ways: 1) free reach anthropometrics, 2) fitting trials and 3) as an independent variable in the biomechanic and psychomotor studies. Furthermore, the product evaluation studies in the laboratory and field used mounting height as an independent variable. The results were not entirely conclusive. The fitting trials indicated that the position taken by users in relation to the device in terms of front displacement could be a very important factor in reach performance. In fact, reaching abilities may be based as much on the nature of the task as on the arm length of the individual. Naturalistic studies or contrived laboratory experiments should be conducted to determine how users position themselves with respect to different devices or equipment. It would be expected that users generally stand back from any device that requires vision to use. They may also stand back from other devices, similar to the way stair users keep a "buffer zone" between them and the wall of a stairway. Another variable that could be investigated is the impact of motivation related to the importance of a device. A real device used to satisfy basic needs is likely to engender a greater positive motivation to reach to a certain height than a simulated device whose purpose is not very clear or free reach tasks with no goal.

Future research should include further attention to psychophysics scales. The two scales used in this research were not completely satisfactory. Their sensitivity was not sufficient to identify small differences between devices.

Finally, a great deal of data were collected during the course of this work that have not yet been analyzed. Further analyses with the existing data could be very fruitful. The following are possible uses of the data:

1. item analysis of the interview survey to develop a standardized assessment tool for hand function.

2. multivariate analysis of performance data to further investigate the relative importance of independent variables in use of devices.

3. use of the video anthropometric data to develop a computer graphic model of disabled hands that can then be manipulated by computer simulation to investigate clearances and movement patterns.

4. detailed movement analysis using the video data.

TABLE 1: RECOMMENDED FORCE LIMITS

GRIP SHAPES	ORIENTA-TIONS	MOTION-DIRECTION	FORCES IN kg-f LOW		MEDIUM		HIGH
LARGE BAR	X	PULL PUSH UP DOWN	1.4(3)	**3.1(7)**	6.3(14)	9.8(22)	16.8(37)
LARGE BAR/ LARGE PLATE	Y XY, YZ	PULL	2.2(5)	**5.2(11)**	9.6(21)	17.2(38)	24.6(54)
LARGE BAR/ LARGE AREA	Y	PUSH	1.4(3)	**3.6(8)**	7.0(15)	12.6(28)	21.2(47)
LARGE BAR (CRANK)	X	ROTATION	1.4(3)	**3.6(8)**	8.0(18)	17.0(38)	27.2(60)
SMALL PLATE	ALL	ALL	0.7(2)	**1.8(4)**	3.5(8)a	6.8(15)a	12.1(27)a
SMALL AREA DISCS SPHERES	ALL	ALL	0.6(1)	**1.5(3)**	3.0(7)	4.0(9)b	7.0(15)b
SMALL BARS	X,Z	ROTATION	**0.7(2)**	1.7(4)	3.4(7)	6.1(14)	8.9(20)

a: reduce by 50% for pull direction; reduce by 25% for up direction

b: increase by 67% for 2" spheres; increase by 75% for areas at heights of 1000 mm (39.4 in.)

Notes: Small bars are from 13 - 25 mm (0.5 - 1.0 in. in cross section); small areas and plates are less than 25 mm (1 in.) wide; values in bold face type should be used for minimum recommendations.

Original measurements/recommendations were made in metric and converted to English units then rounded to the nearest pound.

TABLE 2: CONTROLLED TESTING RESULTS COMPARED TO PRELIMINARY RECOMMENDATIONS

KEY: + = outside range; - = within range; 0 = at or close to threshold value

DEVICE (PIN)	SUCCESSFUL OPERATION (In %)	HEIGHT	ACCESS SPACE	FORCE	CORRECT PREDICTION
ARCH BUILDING					
TELEPHONE RECEIVER (AA4a)	89.7	+	-	0	YES
TELEPHONE NUMBER PAD (AA4b)	79.5	+	-	0	YES
TELEPHONE COIN SLOT (AA4c)	77.5	+	-	NA	YES
TELEPHONE COIN RETURN (AA4e)	76.3	-	-	NA	YESd
PUSH BAR DOOR HANDLE (AC1)	89.7	-	-	+(50TH)	YES
DOOR PULL (AA19)	73.7	-	-	+(25TH)	YES
ELEVATOR CALL BUTTON (AB1)	97.4	-	-	0	YES
ELEVATOR FLOOR BUTTON (AB2)	94.7	+	-	-	NO
WATER FOUNTAIN HANDLE (AD22)	95.0	-	-	+(10TH)	NO
RESTROOM DOOR PULL (AC19)	92.3	-	-	+(10TH)	NO
TOILET FLUSH VALVE (AD34)	71.8	-	+	+(10TH)	YES
FAUCET HANDLE (AD25)	84.6	-	-	+(10TH)a	YES
MANAGEMENT BUILDING					
EXTERIOR DOOR PULL HANDLE (BA4)	69.8	-	-	+(25TH)	YES
WATER FOUNTAIN HANDLE (BA11)	95.2	-	-	+(10TH)	NO
RESTROOM DOOR PULL (BA12)	92.9	-	-	+(10TH)	NO
TOILET FLUSH VALVE (BB24)	83.3	+	-	+(10TH)	YES
FAUCET HANDLE (BA18)	87.5	-	-	+(10TH)	YES
ELEVATOR CALL BUTTON (BA8)	95.0	-	-	-	YES
ELEVATOR FLOOR BUTTON (BB31)	95.0	-	-	-	YES
PUSH BAR DOOR HANDLE (BA6)	82.9	-	-	+(50TH)	YES
MARTA STATION					
ELEVATOR CALL BUTTON (DB16)	97.4	-	-	-	YES
ELEVATOR FLOOR BUTTON (DB13)	92.7	-	-	+(10TH)b	NO
ASSISTANCE TELEPHONE (DC5)	92.7	0	-	-	YES
FARE CARD SLOT (DA7)	95.1	-	-	NA	YES
COIN SLOT (DA6)	95.1	-	-	NA	YES
FARE CARD RETURN (DA1)	92.5	-	-	NA	YES
FARE GATE (DA16)	84.3	-	?	+(10TH)	YES
POST OFFICE					
EXTERIOR DOOR PULL/PUSH (YA1)	65.9	-	-	+(25TH)	YES
STAMP MACHINE (YA2)					
COIN SLOT (YA2)	59.0	+	-	NA	YES
SELECTION BUTTON (YA2b)	67.9	+	-	-	YES
STAMP REMOVAL (YA2c)	56.7	+	-	NA	YES
MAIL SLOT (YA3)	94.6	-	-	NA	YES
P.O. BOX (YA4)	77.0	0	-	?	?
SHEPHERD SPINAL CENTER					
ELEVATOR CALL BUTTON (QB4)	97.5	-	-	-	YES
ELEVATOR FLOOR BUTTON (QB5)	94.9	-	-	-	YES
DOOR KNOB (QC3)	73.2	-	-	?	YES
RESTROOM DOOR PULL (QC13)	90.0	-	-	+(10TH)c	YES
TOILET FLUSH VALVE (QA1)	82.9	+	?	+(10TH)	YESe
FAUCET HANDLE (QA10)	95.2	-	-	-	YES
WATER FOUNTAIN HANDLE (QD1)	100.0	-	-	-	YES
DOOR HANDLE (QC12)	97.6	-	-	-	YES
DOOR PUSH BAR HANDLE (QC5)	73.8	-	-	+(25TH)	YES

NOTES: a: VARIABLE FORCE MAX VALUE USED; WITH SMALL VALUE, FORCE WOULD BE ACCEPTABLE AND SUCCESS RATE WOULD BE 90%. b: EXCEEDED 10TH PERCENTILE VALUE ONLY SLIGHTLY. c: EXCEEDED 10TH PERCENTILE VALUE ONLY SLIGHTLY AND ONLY 10TH PERCENTILE COULD NOT OPERATE. d: WAS DIFFICULT TO USE DUE TO DEVICE DESIGN (SMALL GRIP CLEARANCE). e: BELOW MINIMUM HEIGHT – WAS PRIMARILY A PROBLEM FOR WHEELCHAIR USERS.

HANDS-ON ARCHITECTURE

PART II

RECOMMENDATIONS FOR STANDARDS

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12/17/1986

PREFACE

This technical assistance document is based on the results and findings of the Hand Anthropometrics Project (Contract No. 300-84-0247), created to develop an information base for designing products that are used in buildings and intended to be manipulated by hand. The study focused on the abilities of people with disabilities affecting hand strength and coordination, a group for which there is a lack of human factors design data.

The citations to volume, part and section in this document refer to the three-volume final report of the project, *Hands-On Architecture.* Volume One, the main research report, summarizes the literature review and presents the conceptual framework for organizing the research and findings. Volume Two presents a method and data for improving design of buildings consistent with hand and arm abilities of persons with disabilities. Volume Three, the basis for this technical assistance document, contains an Executive Summary of the project and a set of recommendations or guidelines that can improve building design.

The complete research report can be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22164; or call (703) 487-4650. Specify order number PB90170861/AS.

HANDS-ON ARCHITECTURE
RECOMMENDATIONS FOR STANDARDS

TABLE OF CONTENTS **PAGE NUMBER**

RECOMMENDATIONS

Concept

This report provides recommendations for enforceable accessible design standards for architectural products that are intended to be used by the hand. In keeping with the jurisdiction of the Architectural Barriers Act, (P.L. 90-480) the scope of the recommendations is limited to products built into buildings as permanent fixtures. The recommendations could also provide guidance for design or selection of office furniture and equipment, appliances, tools, and other manipulated objects that are found in buildings on a temporary basis.

The recommendations are based on two sources of information. First, general human factors design principles and specific data bases generated through human performance research with people with disabilities. The second source consists primarily of the results from laboratory and field research conducted as part of the Hand Anthropometrics Project.

There are two kinds of research data that are helpful in generating design standards: directly observed performance data such as the amount of force an individual can exert or his or her reaching abilities, and response data obtained from users of products.

In developing these recommendations, both types of data were used. First, data on observed performance were reviewed to identify the extent to which research subjects could accomplish various tasks related to the use of products. Tentative criteria were developed based on accommodating at least 90% of the sample in terms of performance in the laboratory. The cost impact of these criteria was estimated by assessing the number of products tested in the laboratory and field that did not "comply". About 20% of the field products and over 50% of the laboratory products did not "comply," yet most of these products had been proven usable. We then set new criteria based upon the 25th percentile level of performance for selected variables in the basic laboratory research. A user response rate of 40% in terms of negative user evaluation was the bottom line. In addition, recommendations were never relaxed to the point that products that had observed performance rates of less than 90% for the research samples would "comply." After relaxing the criteria levels as much as necessary to meet these objectives, a qualitative cost analysis of the products not meeting the criteria was performed to identify the cost impact of the proposals.

The format, organization and illustration of the recommended criteria were designed to allow the greatest ease in implementation. Rather than develop specific criteria for hundreds of different types of products, three sets of criteria were developed:

1. general criteria that apply to all devices;

2. additional criteria that apply to individual classes of devices with specific types of devices within each class;

3. identification of important equipment that typically includes several devices with cross-referencing to appropriate general and specific criteria.

This approach kept the criteria from being voluminous. Moreover, the inclusion of general and categorical approaches reduces the likelihood that specific products would not be covered through omission and insured application to new products not yet introduced.

Implementation

A draft of the recommended accessible design standards was discussed with two local code officials to identify enforcement problems. The following problems in implementation were identified by this review:

1. building design documents do not normally show dimensions or other attributes of building products;

2. architects and other designers do not have access to information on many specific dimensions and the force of activation for most products;

3. building code officials do not have the expertise nor the time to evaluate the hundreds of operable devices that may be found in a building either before or after construction;

4. many products are changed or replaced over the lifetime of a building; it would be extremely unwieldy to require approval for every minor replacement or change.

It is recommended, therefore, that, except for the requirements for use clearances and reach limits, the other criteria be implemented in a manner similar to product approval for other aspects of design such as life safety. A certification procedure should be developed through which individual products, having once been submitted and evaluated by a responsible authority, could receive certificates of compliance. Architects could then require such a certificate as part of their specifications and design review officials would require only a label as evidence of that certificate in order to approve any product.

A certification procedure could be implemented in many ways. Three possible models are:

1. certification by an independent laboratory

2. Federal approval through agencies such as the General Services Administration (GSA) or Veterans Affairs (VA)

3. listing of acceptable products in model codes or state building code supplements

In the first model, a voluntary standard could be developed through ANSI to accompany the ANSI A117.1 standard. It would include not only design requirements such as presented here, but also standardized procedures for evaluating products against those requirements. In the development of the standard, a network of certifying organizations such as Underwriters Laboratories, Pittsburgh Testing Laboratories, the National Bureau of Standards, or even professional firms or advocacy organizations could be recruited that would be willing and able to undertake the certification program. After adoption of the standard, manufacturers would submit products for evaluation and pay the certifying organizations a fee to cover the cost of each review. Upon approval, a certificate would be granted. The manufacturers would then include information on certification in their product literature and a label on the product itself. This approach is now used for certifying fire safety characteristics, such as flame spread and smoke generation, of many products.

The second approach would utilize the procurement procedures of the Federal government. The Federal agencies could require a one-time review and certification of all products included in Federally funded new construction or significant renovation or rehabilitation. After obtaining initial approval from any one agency, each product could be added to a centralized list of certified products. Architects, interior designers or facility managers could then choose products off the list. Or, manufacturers could include information in their product literature indicating that approval had been obtained. An agency or architect could check a master list if necessary. The cost of such a program could be borne by the Federal government, by product manufacturers on a fee-for-service basis, or shared.

The third approach would utilize the same process currently in use by model building code groups and some state codes. Once a product is reviewed by a centralized code body, a certificate of acceptability would be granted. A label and product literature would then be used for local code review as in the first approach.

The ATBCB could, if it was within its statutory authority, play a central role in each of these approaches by serving as the coordinating body for establishing the process, maintaining records on certified products and providing quality control.

Priorities

As currently designed, some operable devices are more difficult to use than others. The user response data collected through the Hand Anthropometrics Project provided insight on the relative difficulty of many different devices. From these data, priorities for applying the recommended standards were developed (see Figure A). If, in the process of implementing the requirements, it becomes necessary to focus efforts on a narrower range of devices than presented here, the list of priorities should be used to insure that the most important issues are addressed.

PRIORITIES FOR APPLICATION

Priority:	Product Type:
First	shower heads and shower/bathtub controls; locks for doors and windows; window opening devices, e.g., cranks; door opening devices, e.g., knobs; vending machines
Second	thermostats; paper dispensers; soap dispensers; switches; grab bars
Third	faucet controls; cabinet/drawer pulls; water fountain controls; appliance controls; handrails

Figure A

1.0 GENERAL REQUIREMENTS

1.1 Scope

These requirements apply to all operable devices incorporated into buildings on a permanent basis, either as part of the initial design or in substantial rehabilitation or renovation, that are intended for use by the general public, residents or general employees with the exception of manufacturing equipment and devices intended to be operated solely by maintenance or service personnel (see Table 3.2). Manufacturing, maintenance and service related devices, however, may fall under the jurisdiction of laws related to equal opportunity in employment. In such cases, the requirements found here can be used as a guide but should be supplemented by other more specific requirements for scope of application.

1.2 Use clearances

The minimum clear floor or ground space required to approach an object is 30 inches (762 mm) by 48 inches (1220 mm) (see Figure 1.2a). (For a side approach, the 30 inch (762 mm) clearance should be set back from the device by 6 inches (152 mm). The use clearance must be located on center with the device. Knee clearance for wheelchair use may overlap the use clearance by 24 inches (610 mm) maximum (see Figure 1.2b) for the front approach. This overlap is preferred because it reduces reach distance. The height of any obstruction shall be 36 inches (914 mm) maximum (see Figure 1.2d). Door swings shall not impede access to the required use clearance for any device located within their vicinity.

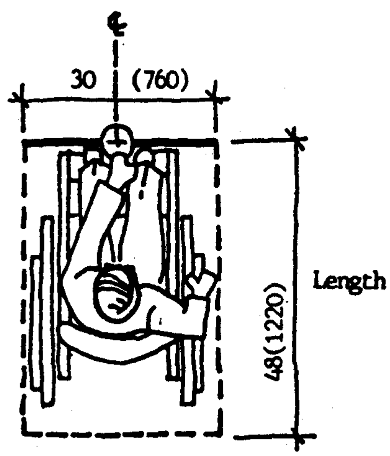
Rationale: Research findings showed that the 30 inch (762 mm) width will accommodate 90% of the study sample for front approaches. When using devices, ambulatory and non-ambulatory people generally position their shoulder to one side of the object to be used, left side for left-handed people and right side for right-handed people. Door swings could obstruct access as a door is opened. Requirements in the existing ATBCB Guidelines and the other accessibility standards cover actual clearances needed to open doors, including access to door openers themselves.

Cost Impact: The side displacement varies with the type of device used but does not exceed 15 inches (380 mm). For side approaches, 6 inches (152 mm) was needed by the 10th percentile group to have enough room for accurate use of the device. Most people would stand even further back but a larger value would put devices beyond the reach of some people. Research findings indicated that wheelchair users position themselves so that the shoulder of the hand being used is displaced to the side of the device when using a side approach. The actual displacement varies considerably but the 48 inch (1220 mm) width and the location of a device at the centerline is consistent with median values. Using the 10th and 90th percentile values would result in extremely large clearances because device locations would be off center with the clearance area. The 48 inch (1220 mm) clearance will accommodate 90% of the study sample for front approaches.

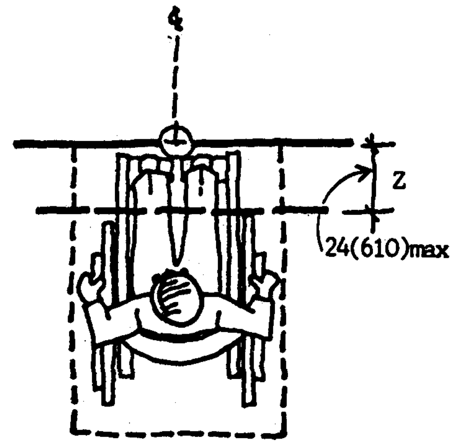
Figure 1.2

USE CLEARANCE:

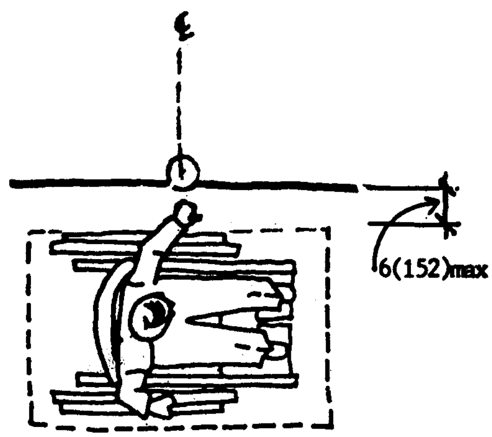
GENERAL REQUIREMENTS



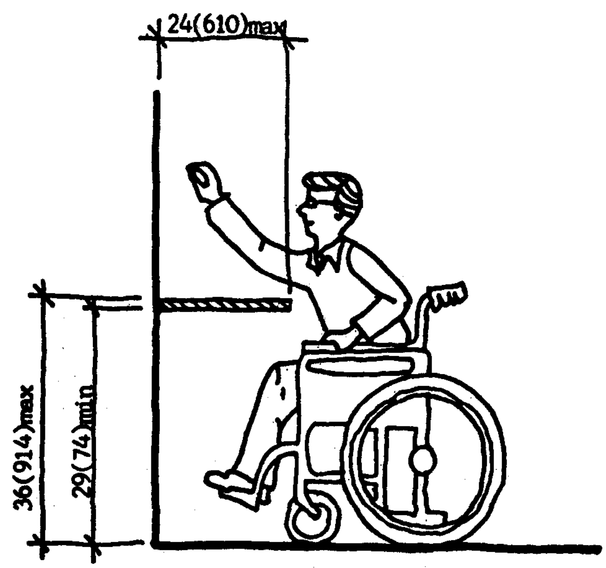
a. Min Clear Floor or Ground Space



b. Knee Clearance Overlap Front Approach



c. Side Approach Maximum Side Reach



d. Max Height and Depth of Obstruction

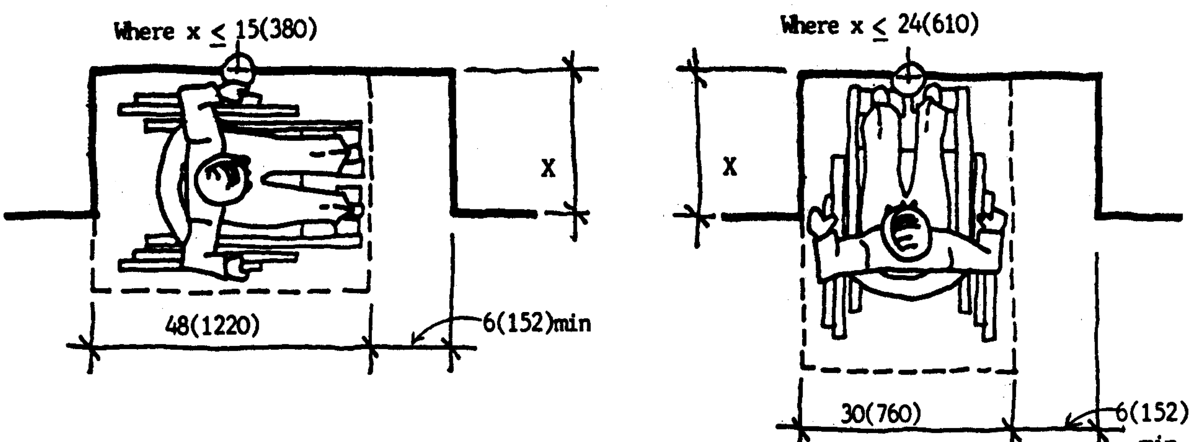
1.3 Access to Use Clearances

At least one full unobstructed side of the use clearance shall adjoin or overlap an accessible route or adjoin another use clearance. Any device located in an alcove or other space confined on three sides shall be increased in size as in Figure 1.3a and 1.3b. Dead-end spaces shall have a turn-around area. This area shall allow either a 180 degree U-turn or a backward T- or L-turn in a wheelchair when leaving the device (see Figure 1.3c and 1.3d).

Rationale: Not only must devices be accessible, but there must also be enough space to maneuver out of the immediate area in a wheelchair. The tolerances in Figures 1.3a and b are consistent with the ANSI A117.1-1980 Standard, ATBCB Guidelines and UFAS. The tolerances in Figure 1.3c are based on data from Steinfeld, et al., 1979.

Figure 1.3

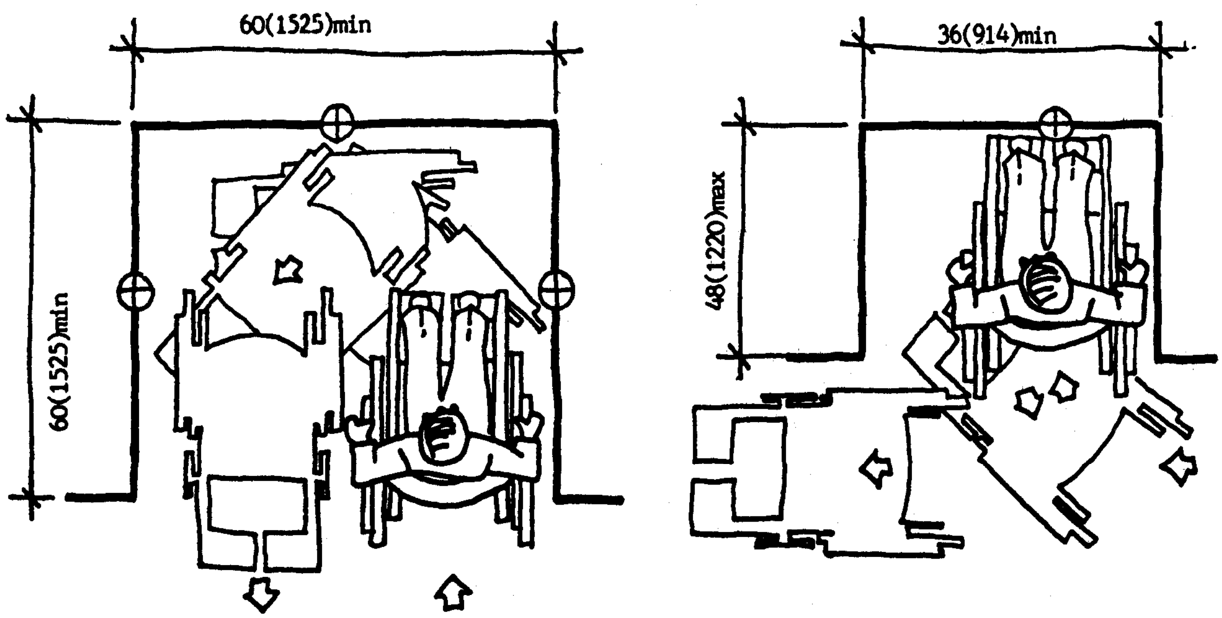
ACCESS TO USE CLEARANCES



a. Alcove – Side Approach

b. Alcove – Front Approach

Additional Maneuvering Clearance for Alcoves



c. 180° U-Turn in Alcove/Dead End Space

d. Backward L-Turn in Alcove/Dead End Space

Turning Clearances for Alcoves

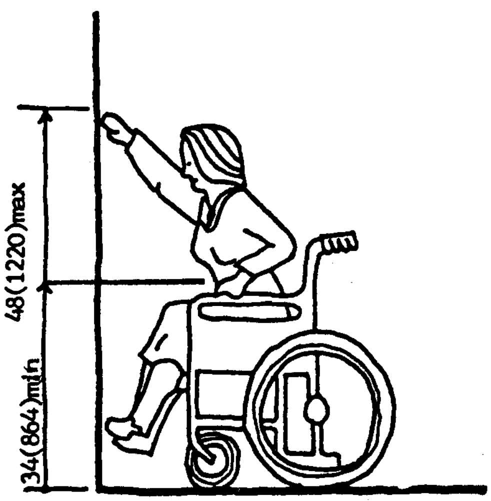
1.4 Reach Limits

The maximum height to an operable device shall be 48 inches (1220 mm) to center above the walking surface with one exception. For devices that can be operated with a flat hand push or finger push and that require 1.5 lb (0.7 kg-f) or less to operate, a 54 inch (1372 mm) maximum height is acceptable (see Figure 1.4a and 1.4b). The minimum height to an operable device shall be 34 inches (864 mm) on center (see Figure 1.4a and 1.4b). Within these ranges, the distance between an object and the adjacent edge of a use clearance may vary with the height of the operable device as shown in Figure 1.4c and 1.4d.

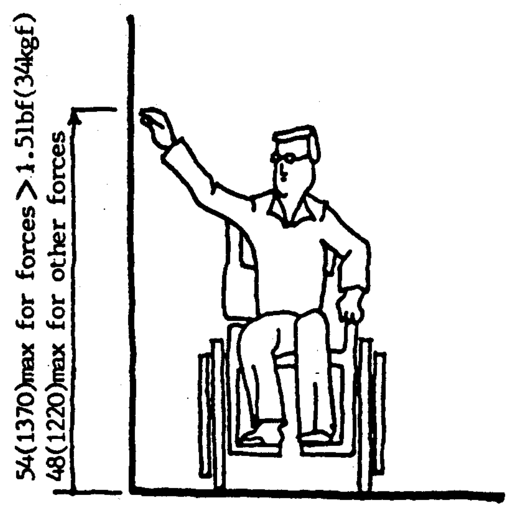
Rationale: Research findings demonstrated that these limits will accommodate 90% of the study sample, including 90% of the wheelchair users. Most wheelchair users have to bend at the waist to reach over their toes. Thus, forward reach lifts for wheelchair users are more difficult since bending lowers the shoulder and the feet obstruct access to the lower range. The research findings indicated that devices above 48 inches (1220 mm) were often impossible for more than 20% of the research sample to use with the exception of devices that required only small amounts of force and no opposing grip to operate. The distance between an obstruction or recessed area and the adjacent edge of a use clearance can vary with the height of a device since the horizontal component of reach increases as the vertical component is reduced.

Figure 1.4

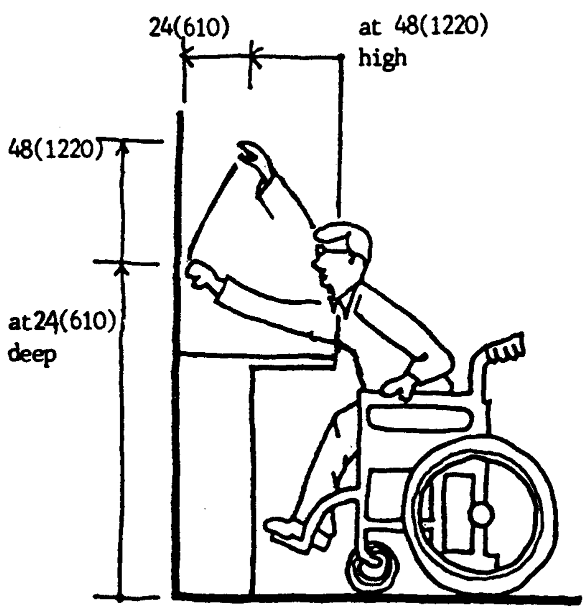
USE CLEARANCES VARIATIONS



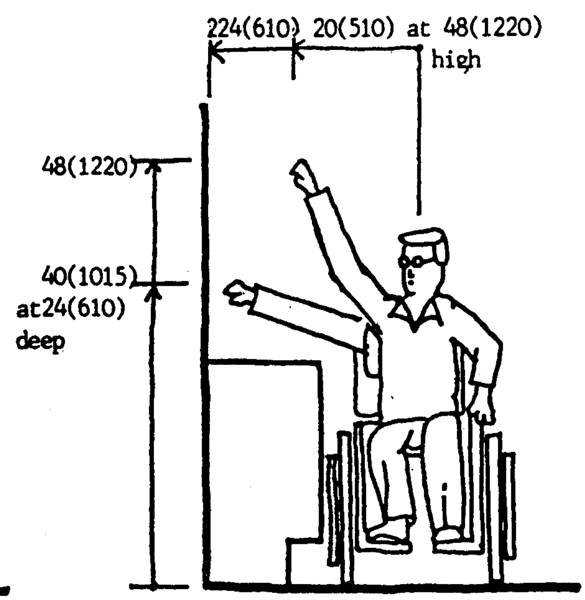
a. Forward Reach Heights



b. Side Reach Height



c. Front Reach Limit



b. Side Reach Limit

1.5 Grip Limits

All operable devices in accessible spaces shall comply with at least one of the grip limits shown in Table 1.5 although Sections 2.2 - 2.6 impose further limitations. Figure 1.5a illustrates the seven grips. Figure 1.5b illustrates how each dimensional requirement is determined. Operating forces shall be measured at the midpoint of the grip length (see Figure 1.5c). Grasp space is illustrated in Figure 1.5d. For those devices in which secondary objects are used in conjunction with a device, see Sections 2.3 and 2.4.

Rationale: The values in Table 1.5 will accommodate 90% of the research sample in the use of actual products. For many precision movements, pinch, span and disc grips are preferable if operating forces are low and wrist movement is restricted. Power grips are preferable for using assists. Many disabled people use alternate movements of the hand in place of one or more of the seven basic grips. These alternate movements include using the heel of the hand, back of the hand, knuckles, thumb, and two fists or flat hand. Hook, flat hand and finger push grips are preferred because they do not require opposing finger and thumb movements. Objects designed for these three grips are also much easier to use with the alternate hand movements.

TABLE 1.5: GRIP LIMITS

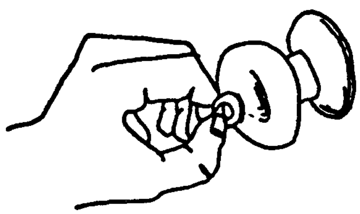
GRIP	MAXIMUM OPERATING FORCE lb (kg-*f*)	MINIMUM/MAXIMUM CROSS SECTION in (mm) CS	MINIMUM GRIP LENGTH in (mm) L	MINIMUM GRASP SPACE in (mm) a, b, c
POWER PULL/PUSH ROTATE (CRANKS)	7 (3.1) 2 (0.7)	0.5 (12) TO 1.7 (43)	5.3 (135)	a: 2.8 (70) b: 1.4 (36)
DISC	3 (1.5)	2.0 (50) TO 2.8 (72)	0.8 (20)[b]	a: 2.0 (50) b: 1.8 (46)
SPAN	3 (1.5)	2.1 (54) MAX	0.9 (23)[b]	a: 2.8 (72) b: 1.4 (36)
HOOK[a]	11 (5.2)	2.1 (54) MAX	3.5 (88)	a: 2.7 (69) b: 1.4 (36)
PINCH	4 (1.8)	0.1 (3) TO 1.2 (31)	1.0 (25)[b]	a: 6.2 (158) b: 2.5 (64)[d] c: 4.0 (101)[e]
FINGER PUSH[a]	3 (1.5) 0.2 (0.1)	NA NA	0.8 (20)[b] NONE	0.7 (18)[b] 0.7 (18)[b]
FLAT HAND PUSH[a]	8 (3.6)	NA	a: 7.7 (196) b: 3.5 (88)	a: 7.7 (196)[g] b: 6.6 (167)[h]

NOTES: Original measurements taken in metric and converted to English units. Pounds were rounded to nearest whole number where possible.

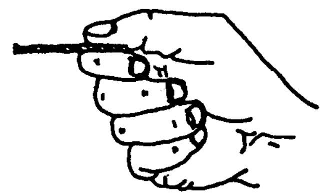
[a]Preferred for all devices; required for handles. [b]Based on anthropometric data for population at large (see Diffrient, et al., Humanscale)
[c]a: grip clearance; b: finger clearance. [d]Clearance for thumb. [e]Width of fist. [f]If practically no force is required, an area can be very small with practically no impact on usability. [g]Vertical clearance. [h]Horizontal clearance.

Figure 1.5a

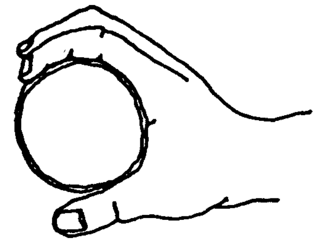
PROJECT GRIP TYPOLOGY



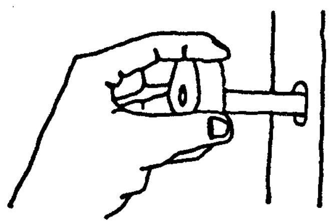
1. Pinch



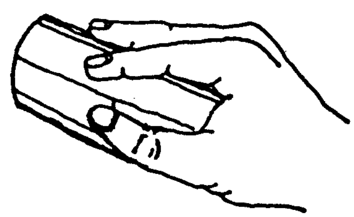
1. Pinch



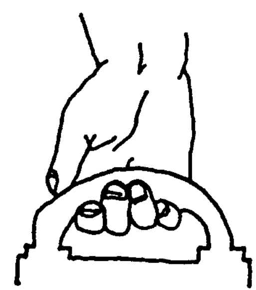
3. Span



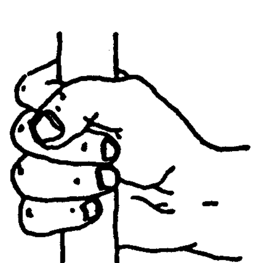
2. Disc



2. Disc

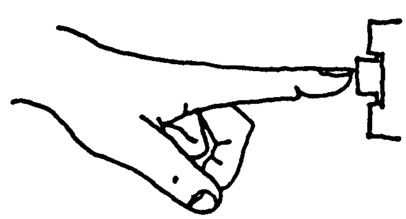


4. Hook



5. Power

6. Flat Hand Push



7. Finger Push

Figure 1.5b

GRIP SHAPES WITH SIZE PARAMETERS

KEY:

- P: PERIMETER
- CS: CROSS SECTION (diameter) (may be maximum and minimum cross section)
- L: Length of Grip Area (may be more than one)

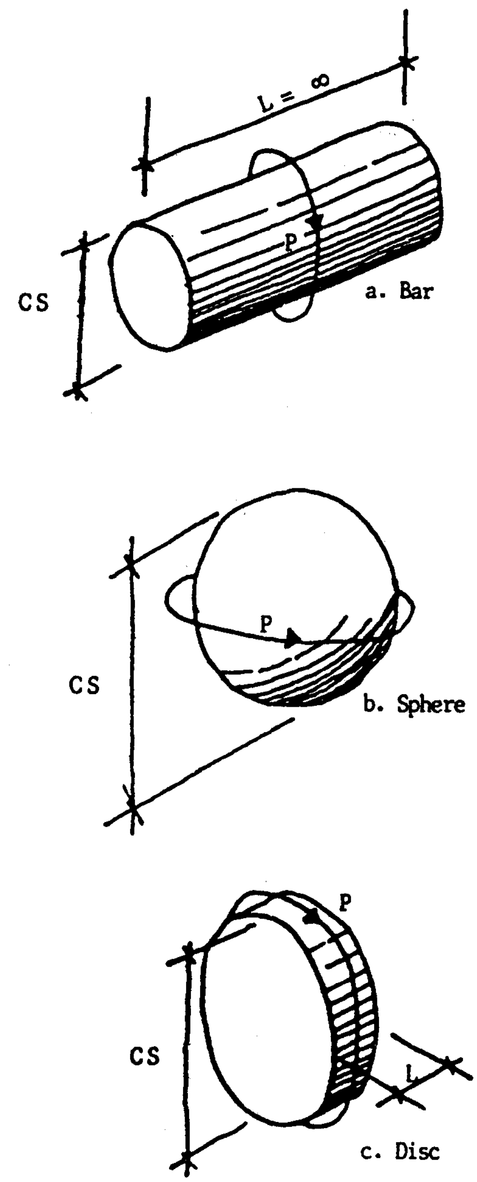


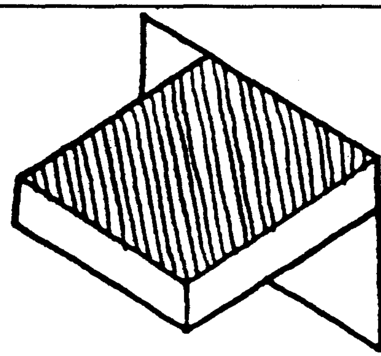
Figure 1.5b: Grip Shapes with Size Parameters, (continued)

KEY:

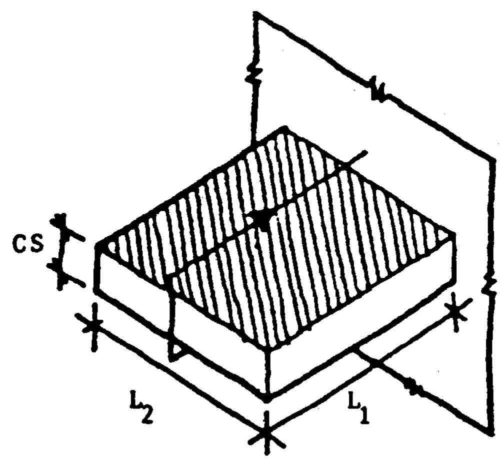
P: PERIMETER

CS: CROSS SECTION (diameter) (may be maximum and minimum cross section)

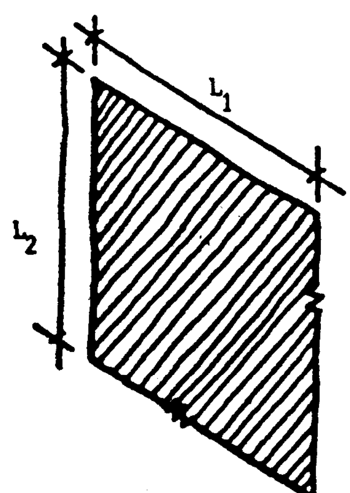
L: Length of Grip Area (may be more than one)



d. Plate



d. Plate

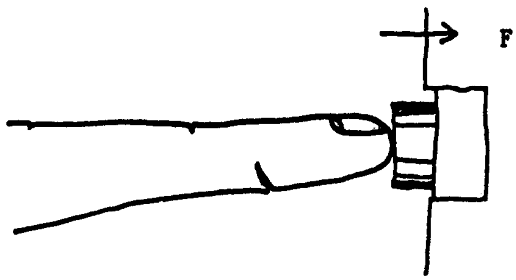


e. Area

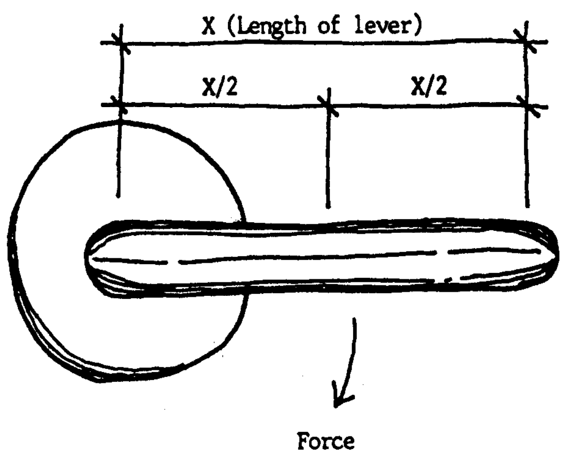
Shaded areas are gripped by the hand

Figure 1.5c

OPERATING FORCE MEASUREMENTS

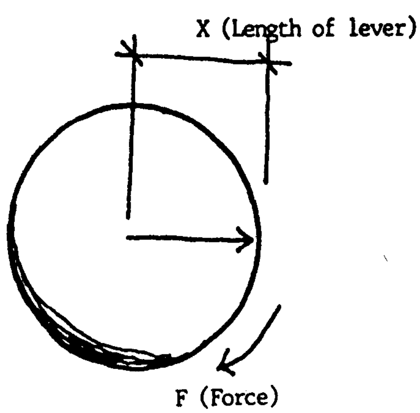


F = direct Force



$$\text{Torque} = \frac{X}{2}(F)$$

$$F = \frac{2(\text{Torque})}{X}$$

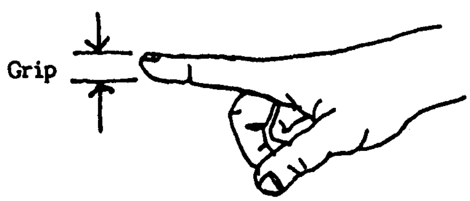


$$\text{Torque} = X(F)$$

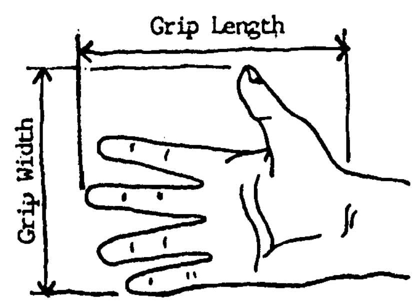
$$F = \frac{\text{Torque}}{X}$$

Figure 1.5d

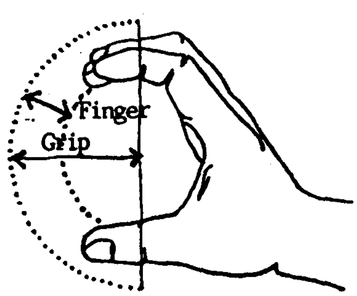
GRASP CLEARANCES



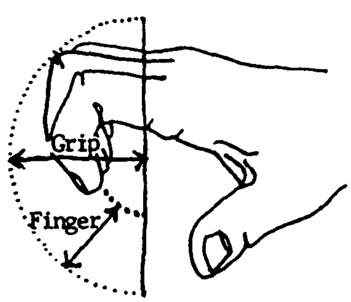
Finger Push



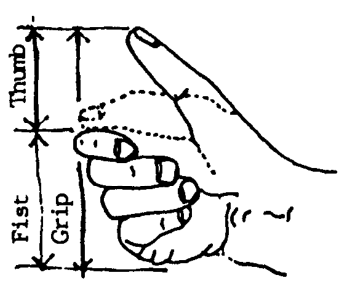
Flat Hand Push



Power, Span



Disc, Hook



Pinch

2.0 OPERABLE DEVICES

2.1 General

All devices falling under the scope of these requirements (see Section 1.1) and described in Sections 2.2 - 2.6 must be located within the reach limits described in Section 1.4 and comply with the requirements for Use Clearances in Section 1.2 and Access to Use Clearances in Section 1.3. Requirements in Sections 2.2 - 2.6 for specific devices are in addition to the General Requirements for grip limits in Section 1.5. Any device may be automatically operated. Controls for power operation shall comply with Sections 2.2 and 2.5 as applicable.

Rationale: Specific types of devices have requirements beyond those found in Section 1.4 Automatic operation is preferable, in most cases, to direct user manipulation. Power operation requires use of electronic controls, and often handles as well; thus, except where activation is controlled by sensors such as photo-electric cells or magnetic detectors, these controls and handles must also comply.

2.2 Additional Requirements For Electronic Controls

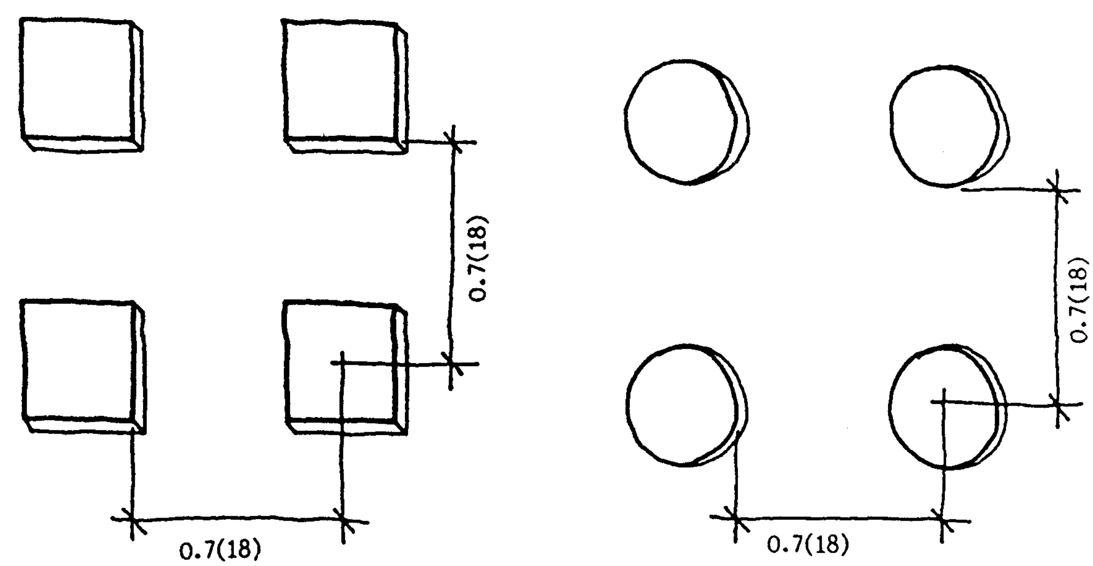
The minimum space between electronic controls shall comply with Table 2.2 and measured as in Figure 2.2. Where controls are clustered together, such as an elevator control panel or telephone button array, the height of the highest control shall be within the reach limits of Section 1.4. The minimum hand grasp space shown in Table 1.5 shall apply throughout the movement distance of an electronic control. Throughout its full movement distance, an electronic control shall not extend beyond the reach limits of Section 1.4.

Rationale: The minimum spacing requirements will accommodate 90% of the research sample. The spacing provides tolerance for inaccuracy and limited control due to deficits in psychomotor performance. However, such problems are relevant only for small controls (e.g., less than one finger width wide). Thus, the measurement of spacing is made from the center of the device. The spacing requirements also account for finger clearances required for moving the hand using disc or pinch grips. They accommodate 90% of the research sample. To use controls fully, they must be within reach and have sufficient hand clearance within movement range at all times.

TABLE 2.2: SPACING OF ELECTRONIC CONTROLS

DEVICE:	GRASP SPACE:
Buttons/Push Plate	0.7 inches (18mm), center to center
Knobs	1.8 inches (46 mm), outside to outside
Slides	2.0 inches (50 mm), center to center
Toggles	2.0 inches (50 mm), center to center

Figure 2.2: SPACING OF BUTTONS



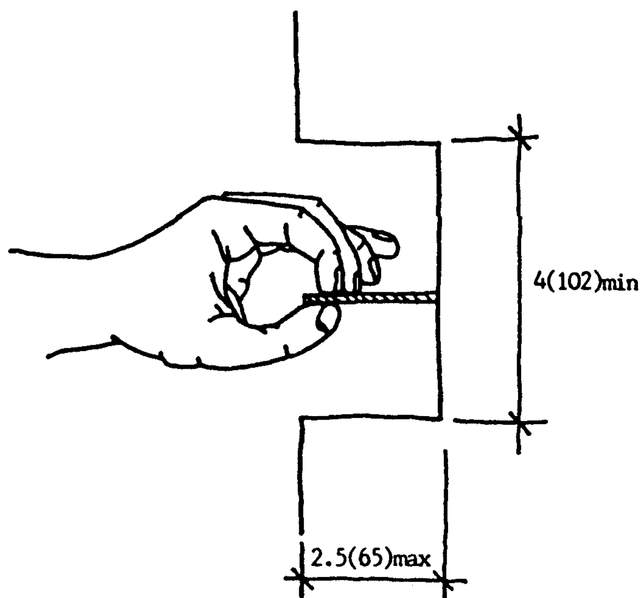
2.3 Additional Requirements for Dispensing Devices

At openings where objects are extracted from dispensers using pinch, power, span or disc grips, clearances shall be at least as large as those shown in Figure 2.3. For calculating reach limits, the depth of an opening shall be considered as an obstruction or recess (see Sections 1.2 and 1.4). Forces required for extracting objects from dispensers shall be no greater than 4 lb (1.8 kg-*f*).

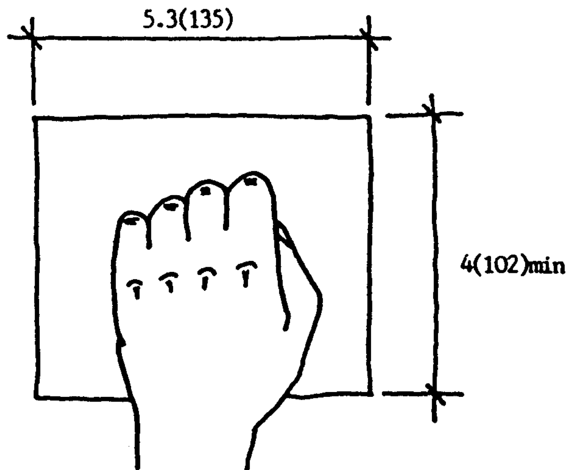
Rationale: These requirements accommodate the sizes of the above grips for 90% of the research sample.

Figure 2.3

CLEARANCES AT DISPENSER OPENINGS



Side View



Front View

2.4 Additional Requirements for Receptacles

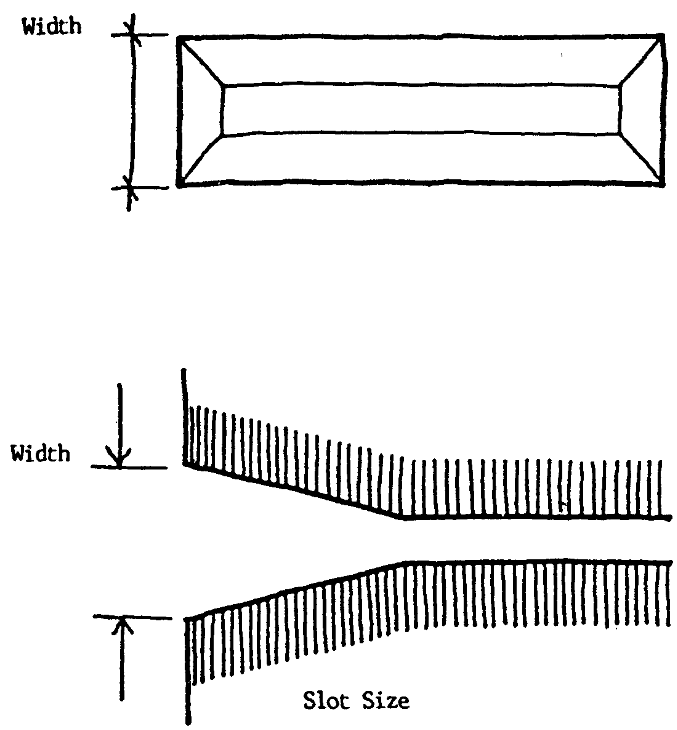
2.4.1 Card and Coin Slots

Coin slots shall be 0.12 inches (3 mm) wide, minimum at the outside surface of the slot (see Figure 2.4.1). Slots in a vertical surface shall be horizontal in orientation (see Figure 2.4.1). Slots in a horizontal surface shall be oriented with the slot length parallel to the user's (see Figure 2.4.1). Space clearances around slots shall comply with those shown in Figure 2.3. If cards are inserted only part way into a slot, at least 1 inch (25 mm) of the card shall remain exposed. The force required to insert a card into a slot shall be no greater than 4 lb (1.8 kg-*f*). The center of a slot shall be used to calculate compliance with reach limits in Section 1.4.

Rationale: These sizes would allow 90% of the research sample to use slots in times that are equivalent with those of able-bodied people. Increasing the slot width would not improve speeds to any great extent. The orientations specified reduce the need to flex, extend or laterally deviate the wrist, a major source of pain for hand-disabled people. The force limits will accommodate 90% of the research sample.

Figure 2.4.1

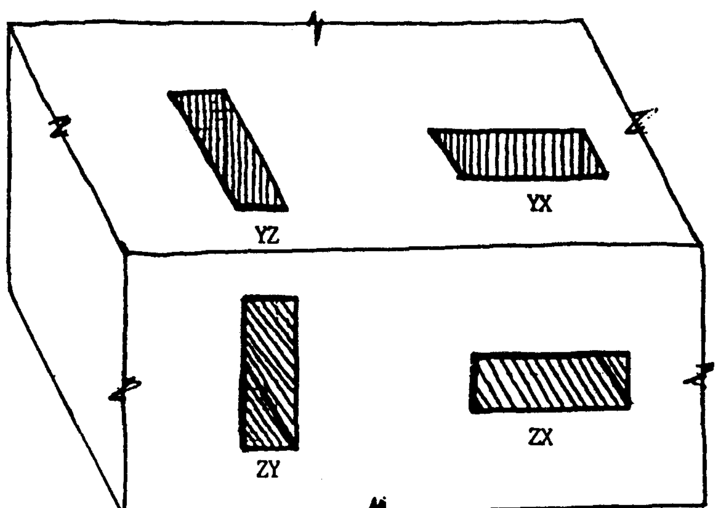
SLOT SIZE AND ORIENTATION



Slot Size

Coin Slots - Min:

Card Slots - Min:



Slot Orientation

2.4.2 Keyed Locks

The force to turn a keyed lock shall be 4 lb (1.8 kg-*f*) maximum. Space clearances around the keyhole shall comply with those shown in Figure 2.3.

Rationale: Although keyed locks were difficult for 10% of our subjects to use, it is unlikely that they can be eliminated from buildings. Alternatives such as combination locks or magnetic card locks are preferred but are expensive at the present time. It is also unlikely that keyholes could be made wider. Standard key sizes now in use could not be changed without great cost. The use of guiding-type openings would result in the need for longer keys. The force limits accommodate 90% of the research sample.

2.4.3 Other Receptacles

The opening of any receptacle into which a hand must be inserted for use shall be as shown in Figure 2.3. The force required to open a door on a receptacle shall be 8 lb (3.6 kg-*f*) maximum for pushing and 11 lb (5.2 kg-*f*) maximum for pulling. All receptacle doors that must be pulled to open shall have handles complying with Section 2.6. The center of the opening at the point of maximum hand insertion shall be used to calculate compliance with reach limits in Section 1.4.

Rationale: These sizes and forces would accommodate 90% of the research sample.

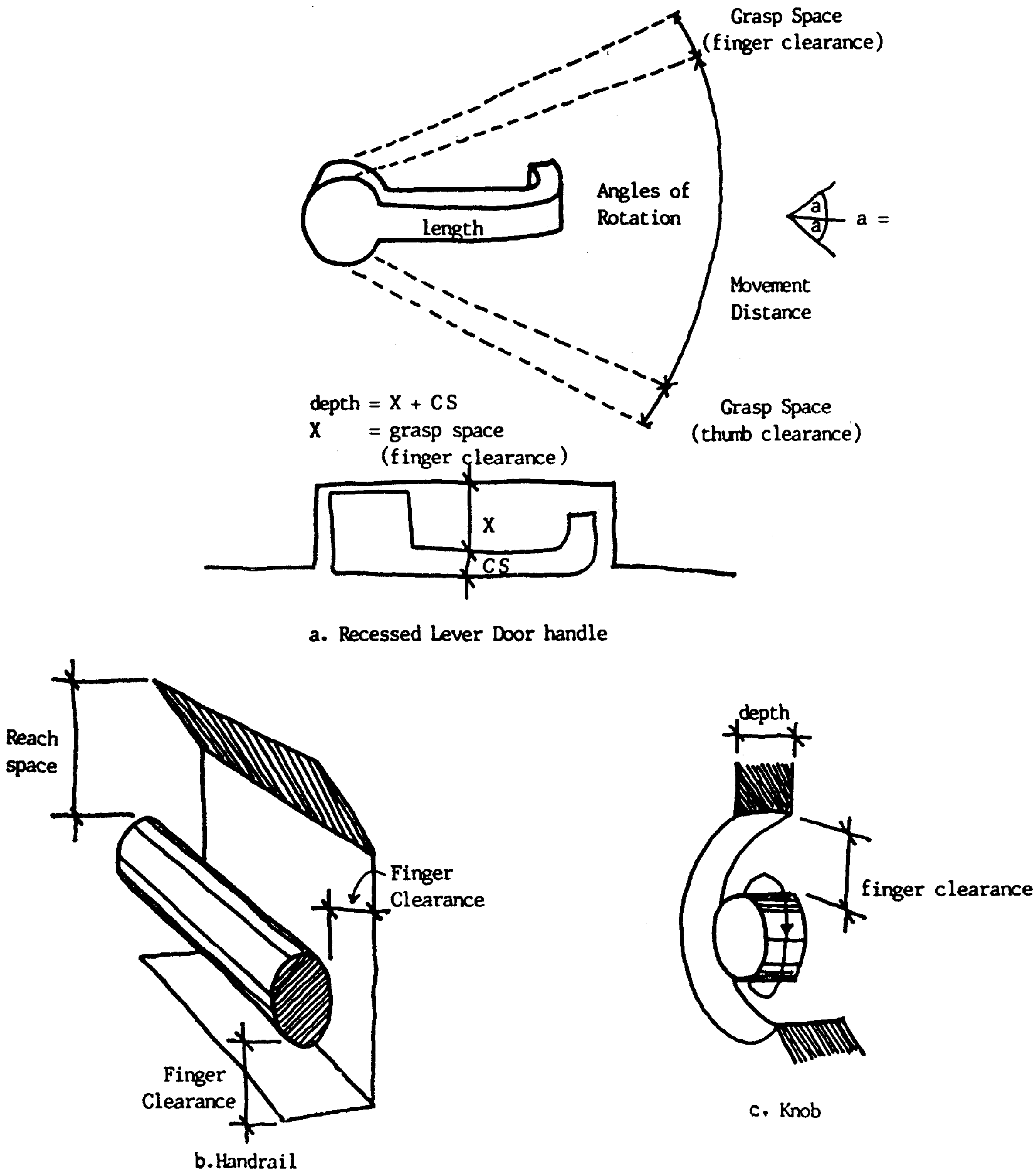
2.5 Additional Requirements for Handles

All handles in accessible spaces of public buildings and entries of accessible dwelling units shall be operable by at least one of the following grips: hook, flat hand or finger push. Design for use by other grips as well is allowable. The minimum hand grasp space shown in Table 1.5 shall apply throughout the movement distance of a handle (see Figure 2.5a, b and c for examples). Through its full movement distance, a handle shall not extend beyond the reach limits in Section 1.4. The minimum edge radius of any handle shall be 1/8 inch (3 mm). The maximum angle of rotation for any handle shall be as shown in figure 2.5a. All handle surfaces shall be free of abrasive textures and sharp elements.

Rationale: To use a handle, it must remain within reach and have sufficient hand clearance throughout its movement range. Many people have difficulty rotating handles because they have limited wrist action or have pain when they flex, extend or laterally deviate their wrists. Cylindrical or bar-shaped handles can be moved with only slight wrist action but grasping and rotating discoids and spheres require considerably more involvement of the wrist even if they are only pushed or pulled. The angles of rotation in Figure 2.5a were comfortable for 90% of the research sample. The edge radius of a handle must not be too small or it will cause pain as it is grasped.

Figure 2.5

PROVIDING GRASP SPACE THROUGHOUT MOVEMENT DISTANCES



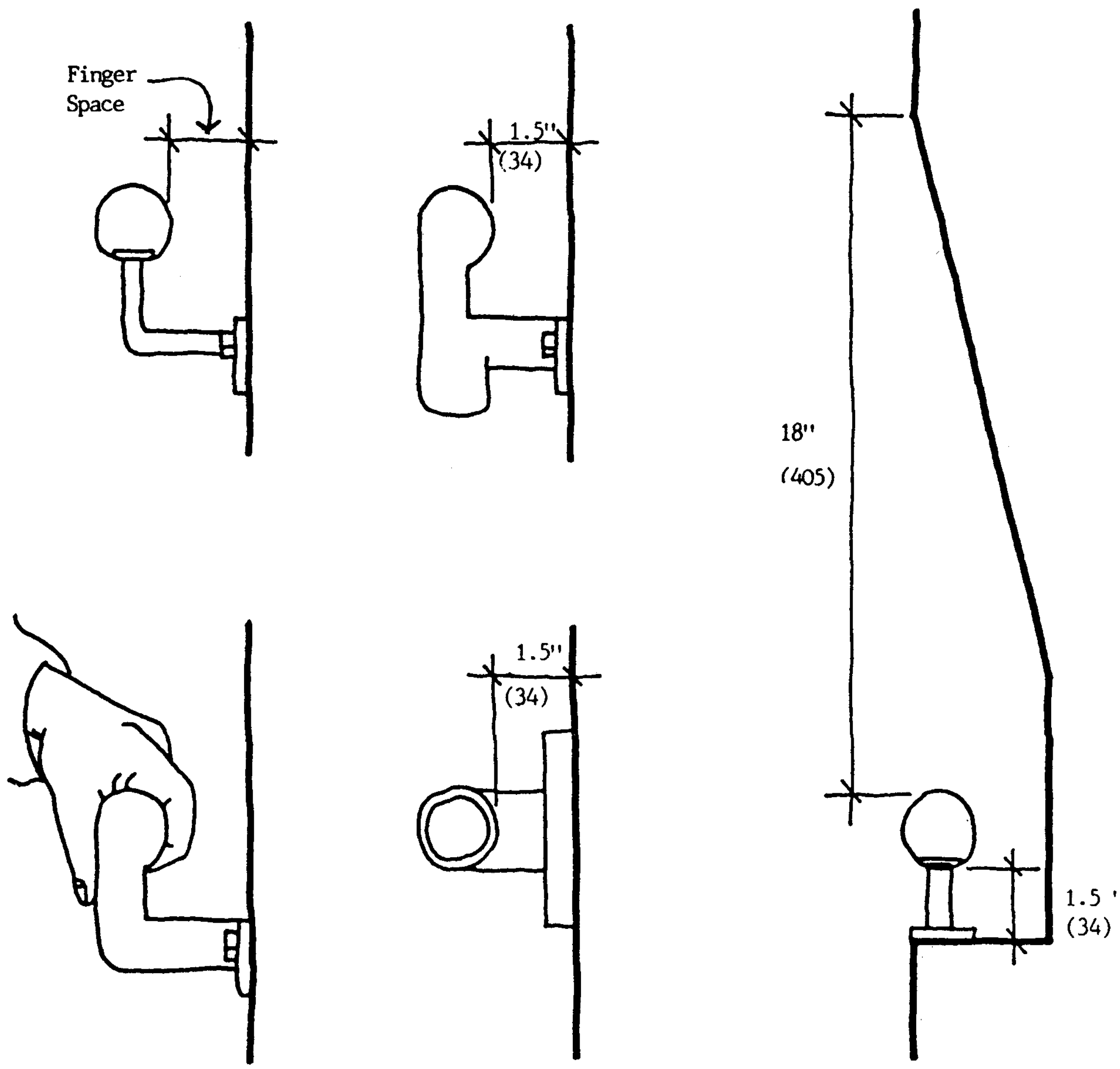
2.6 Additional Requirements for Assists

All assists shall comply with the requirements in Table 1.5 for power grips. The allowable range of cross sections shall be further limited to 1.3 inches (33 mm) minimum. The spacing of grab bars, hand rails and railings to adjacent mounting surfaces shall be as shown in Figure 2.6. All grab bar, handrail and railing sections and their fastening and mounting devices shall withstand a live load of 270 lb (121 kg-*f*) applied in any direction at any part of the object. Grab bars, handrails and railings shall not rotate or move laterally in their fittings. The minimum edge radius for any grab bar, handrail or railing shall be 1/8 inch (3 mm). All gripping surfaces shall be free of abrasive edges and sharp elements.

Rationale: The power grip allows the exertion of maximum strength which is of paramount importance in using assists. Although 90% of the research sample could form a grip around a 0.5 inch (12 mm) cross section, assists are used for support and, therefore, the minimum cross section should be larger than that of a handle. These space clearances are sufficient to accommodate 90% of the research sample using a power grip. Sharp edges on an assist can cause considerable discomfort. The maximum live load that a grab bar, handrail or railing would have to support with respect to building accessibility is the full falling weight of an individual in the 99th percentile range of the population which is 267 lb (120 kg-*f*). Other building regulatory concerns, structural safety requirements (e.g., a crowd leaning against a guardrail) supercede this requirement.

Figure 2.6

HANDRAIL, RAILING AND GRAB BAR CLEARANCES



3.0 EQUIPMENT

3.1 Applicability

All equipment in accessible spaces shall comply with Sections 1.2 - 2.6. Examples of equipment and devices that must comply are listed in Table 3.1. This table is not intended to be inclusive. It is presented as an aid for using the requirements.

3.2 Exceptions

All equipment listed in Table 3.2 need not comply with the requirements (see Section 1.1). This table provides examples only and is not intended to be inclusive. It is presented as an aid for using the requirements.

TABLE 3.1: APPLICABLE EQUIPMENT

EQUIPMENT	DEVICES	CROSS REFERENCES
ELEVATORS		1.2, 1.3, 1.4
	CAR CONTROLS	1.5, 2.2
	CALL CONTROLS	1.5, 2.2
	EMERGENCY COMMUNICATIONS	1.5, 2.2, 2.5
	HANDRAILS	1.5, 2.6
DOORS		1.3, 1.4
	OPENING HARDWARE	1.5, 2.4.1-2, 2.5
	POWER OPERATION CONTROLS	1.5, 2.2, 2.4.1-2
	LOCKS	1.5, 2.2, 2.4.1-2, 2.5
WINDOWS		1.2, 1.3, 1.4
	OPENING HARDWARE	1.5, 2.5
	POWER OPERATION CONTROLS	1.5, 2.2, 2.4.1, 2.5
	LOCKS	1.5, 2.4.1-2, 2.5
PLUMBING FIXTURES		1.2, 1.3, 1.4
	FAUCETS	1.5, 2.5
	FLUSH VALVES	1.5, 2.5
	SHOWER CONTROLS	1.5, 2.5
	SHOWER SPRAYS	1.5, 2.5
	STOPPER CONTROLS	1.5, 2.5
DRINKING FOUNTAINS AND WATER COOLERS	FLOW CONTROLS	1.2, 1.3, 1.4, 1.5, 2.5
APPLIANCES		1.2, 1.3, 1.4
	DOOR AND DRAWER HANDLES	1.5, 2.5
	SETTING CONTROLS	1.5, 2.2, 2.5
VENDING MACHINES, ATMS, FARE MACHINES, PUBLIC TELEPHONES		1.2, 1.3, 1.4
	COIN AND CARD SLOTS	1.5, 2.4.1
	CONTROLS	1.5, 2.2
	DISPENSER OPENINGS	1.5, 2.3
	DOOR AND DRAWER HANDLES	1.5, 2.5
CABINETRY AND STORAGE		1.2, 1.3, 1.4
	DOOR AND DRAWER HANDLES	1.5, 2.5
	LOCKS	1.5, 2.4.1-2
	SHELVES	1.5
	CLOTHES HANGING RODS	1.5
OFFICE FURNITURE		1.2, 1.3, 1.4
	DOOR AND DRAWER HANDLES	1.5, 2.5
	LOCKS	1.5, 2.4.1-2

TABLE 3.2: EXEMPTED EQUIPMENT

1. All equipment in locked mechanical and electrical rooms, closets and cabinets.
2. All equipment above suspended ceilings.
3. Locked thermostats.
4. Power tools and other manufacturing equipment.
5. Adjustment screws, knobs and other devices on appliances hidden by service panels or accessible only by moving equipment out of its intended operating position.
6. Switches in circuit breaker panels or fuse boxes.
7. Switches operable only with special tools in possession of maintenance personnel.
8. All keyed locks for which keys are distributed only to service or maintenance personnel.

4.0 DESIGN IMPLICATIONS

The recommendations for enforceable guidelines and requirements have significant implications for the design of several commonly used and specified products found in buildings. To illustrate these implications, the applicable design criteria for some specific products are summarized below (measurements were originally made in metric, converted into English units and rounded as necessary).

4.1 Card and Coin Slots

- minimum clear floor space for front approach: 30 inches (762 mm) by 48 inches (1220 mm).
- minimum clear floor spaces for side approach: 36 inches (914 mm) by 48 inches (1220 mm).
- located between 34 inches (864 mm) and 48 inches (1220 mm) from the floor.
- in a vertical surface, slots must be oriented in a vertical position.
- in a horizontal surface, slots must be oriented with their long dimension parallel to the user's shoulders.
- minimum dimension width: 0.12 inches (3 mm).

- maximum force required to push or pull object in the slot: 4 lb (1.8 kg-*f*).

- grasp clearance: 2.5 inches (64 mm) at the top side of horizontal slot in vertical surface; 4.0 inches (101 mm) at bottom of horizontal slot in vertical surface and at all other sides.

4.2 Window Hardware

- minimum clear floor space for front approach: 30 inches (762 mm) by 48 inches (1220 mm).

- minimum clear floor space of 36 inches (914 mm) by 48 inches (1220 mm) for a side approach.

- located between 34 inches (864 mm) and 48 inches (1220 mm) from the floor.

- handle must allow either a hook, flat hand, or finger push grip.

- using a small bar or plate (most likely shapes), maximum operable force of 2 lb (0.7 kg-*f*).

- minimum grasp space for a hook grip of 1.5 inches (38 mm).

- maximum angle of rotation: 90 degrees.

- cross section (diameter) of handle (hook grip): 2.7 inches (69 mm) maximum.

- minimum length of handle: 5.3 inches (135 mm).

- grasp clearance: 2.7 inches (69 mm).

4.3 Doors

- approach clearances would be established by existing accessibility standards and codes.

- height of opener 34 inches (864 mm) to 48 inches (1220 mm).

- grip shape must allow a hook, flat hand or finger push grip -- lever opener, door pull or push plate.

- force of opening door would be established by existing accessibility codes and standards (8.5 lb, 4 kg-*f*).

- operating force of handle would be 11 lb (5.2 kg-*f*) maximum if bar (lever opener).

- cross section (diameter) of handle (assuming power or hook grip): 0.5 inches (13 mm) to 1.7 inches (43 mm).

- minimum length of handle: 3.5 inches (88 mm).

- grasp clearance: 2.7 inches (69 mm) grip; 1.4 inches (36 mm) fingers.

4.4 Paper Dispensers

- minimum clear floor space for front approach: 30 inches (762 mm) by 48 inches (1220 mm).

- minimum clear floor space for a side approach: 36 inches (914 mm) by 48 inches (1220 mm).

- located between 34 inches (864 mm) and 48 inches (1220 mm).

- if paper projects out of the device so that it can be grasped directly, maximum force to pull out: 4 lb (1.8 kg-f).

- if a handle is used to control paper flow, it must be operable by a fist, a hook, flat hand, or finger push (e.g., button or large crank that a whole hand can move or a push plate): maximum force of 3 lb (1.5 kg-f) for a button.

- if a hand is inserted into an opening to pull out paper, then the opening must have at least 4 inches (102 mm) by 5.3 inches (135 mm) clearance.

- cross section (diameter) of handle: 2.1 inches (54 mm) maximum.

- minimum grip length of paper projection: 1 inch (25 mm).

- grasp clearance: 2.7 inches (69 mm) for handle; 6.2 inches (158 mm) for paper.

4.5 Lighting Controls

- minimum clear floor space for front approach: 30 inches (762 mm) by 48 inches (1220 mm).

- minimum clear floor space for a side approach: 36 inches (914 mm) by 48 inches (1220 mm).

- located between 34 inches (864 mm) by 48 inches (1220 mm) from the floor.

- button, push plate, knob, slide or toggle acceptable.

- minimum spacing to adjacent controls: 0.7 inches (18 mm).

- maximum force for operation: 3 lb (1.5 kg-f) for knob or plate; 2 lb (0.7 kg-f) if area is used, grip length can be very small.

- minimum cross section (diameter): 0.1 inch (3 mm) for plate; 2.0 inches (51 mm) to 2.8 inches (71 mm) for disc.

- grasp clearance: 6.2 inches (158 mm) for plate; 2.0 inches (51 mm) for knob.

4.6 Handrails and Grab Bars

- minimum clear floor space for front approach: 30 inches (762 mm) by 48 inches (1220 mm).

- minimum clear floor space for side approach: 36 inches (914 mm) by 48 inches (1220 mm).

- height and location required as currently established.

- shape must allow a power grip.

- cross section (diameter): 1.3 inches (33 mm) to 1.7 inches (43 mm).

- maximum perimeter of 5.2 inches (132 mm).

- minimum grip clearance: 1.5 inches (38 mm).

- minimum live load of 270 lb (121 kg-f).

- minimum edge radius of 1/8 inch (3 mm) with no abrasive edges or sharp elements.

- no rotation or lateral movement within fittings.

Cost Implications

After making final adjustments to the recommendations, their cost impact was evaluated by comparing the types of products that would meet the criteria to those that would not. Out of 39 products tested in the laboratory, 12, or 30%, did not meet the final recommendations. Eight of these were judged uncomfortable to use by 40% or more of the subjects. All of the twelve devices were designed to be used with a pinch, finger push or disc grip. Five of the devices were plumbing fixtures and controls. Three were locks and three were dispensers. The last was a window opener.

Out of nine door and window openers, only one did not meet the criteria. Thus there is no cost impact for such devices. There are many available on the market at various price ranges that will meet these recommendations.

The three locks that did not meet the recommendations all required a pinch grip to use. These devices were very common, including the "in the knob" type of twist lock. There are also inexpensive alternatives available for these devices, including the simple push type "in the knob" lock. The latter would be very easy for hand disabled people to use if, when in the closed position, it can be unlocked by opening the latch or by another releasing push. The most uncomfortable device of all to use was the double hung window catch. This is a very common device for inexpensive windows. It is difficult to operate for all people.

Although five of the nine plumbing fixture controls did not meet the recommendations, four of these were similar devices -- all disc shapes that required considerable force to operate and/or required a disc grip to use. There are inexpensive alternatives to all of these devices.

For the dispensers, no problems were discovered for the paper dispensers which required practically no force to operate. The three soap dispensers which all operated on the same principle -- a push pump with a small circular shaped plate -- were all unsatisfactory. This type of dispenser has generally been replaced by the pre-packaged liquid soap dispensers. These require less force to operate and have large pull plates. Thus, there does not seem to be any cost impact for such dispensers.

All the electronic controls were satisfactory. There are many small keypads, however, that would not meet the spacing recommendations. The most serious problem here would be public telephones that have buttons spaced 0.2 inches (5 mm) closer together than the recommendations derived from the laboratory research. The subjects in the field study had no problems using a public telephone. Thus, a reduction in the spacing requirements might be in order.

The cabinet pulls all met the recommendations. Although two of them were difficult to use for about 30% of the subjects, both were unusual and not very sensibly designed. It is unlikely that such designs would be used often.

One aspect of the recommendations that would clearly have a significant cost impact is the clearance for dispenser openings. As found in the field study, the coin return on a public telephone was very difficult to use. This common device would not meet the recommendations.

Although no assists were studied in the laboratory or in the field, the recommendations would not be difficult to meet with a large variety of handrails and grab bars. The maximum cross section (diameter) recommendations would restrict the use of railings with diameters over 1.7 inches (43 mm). Railings of this size are relatively common. However, the recommendations are more flexible than the existing Federal and ANSI standards.

This project did not complete extensive testing of large pieces of equipment with several devices such as vending machines and automatic teller machines. It is conceivable that many vending machines would not comply with the recommendations, particularly those related to reach, coin returns and dispenser openings. The extent of the cost impact for such equipment is difficult to determine without considerably more investigation.

In summary, with a few important exceptions, there should be relatively little cost impact associated with implementation of the recommendations. There is also a good possibility that there are some product types not encountered in this research among which it would be difficult to find many devices that would comply completely. Before adopting these recommendations, it is suggested that considerable effort be invested in communications with industry to discover any unknown problems. Moreover, particular attention should be given to the problem of spacing for keypads and the space clearances of coin returns. These are clearly important issues that have to be addressed.

DEFINITIONS

ASSISTS:	Devices such as handrails, grab bars and railings that are gripped in order to aid in movement or provide support while shifting posture.
AUTOMATIC OPERATION:	A process not requiring direct human interaction to begin and control, such as activation by photo-electric cells, magnetic detection systems or floor-mounted pressure switches.
DISPENSER:	A device from which users extract secondary objects for purposes of use or consumption, such as a paper towel dispenser slot, vending machine openings, or coin returns.
ELECTRONIC CONTROL:	A device that activates or controls a process through electricity, such as a toggle switch, elevator push button or dimmer slide or knob.
EQUIPMENT:	A product that incorporates more than one operable device that often must be manipulated in sequence, for example, a vending machine, door, elevator, or plumbing fixture.
GRASP SPACE:	The space required to form a grip around a device and operate it; the grasp space includes at least two components -- overall grip clearance and finger clearance.
GRIP:	A movement of the hand used to manipulate some object. There are several types, including power, hook, pinch, disc, span, finger push, and flat hand push.
HANDLE:	A device that is gripped in order to move another object to which it is attached or to activate or control a process through mechanical means, such as a door opener, faucet, shower spray, window lock, or cabinet pull.
OPERABLE DEVICE:	A device that can be manipulated by a hand movement for purposes of activating, adjusting or controlling a process related to the general use of buildings. Operable devices include devices in which a secondary object, including but not

limited to coins, cards, keys, and paper products are used in conjunction with the device itself.

POWER OPERATION OR ASSIST: A process utilizing electro-mechanical power that is activated directly and voluntarily by the building user through operable devices such as push buttons, levers or bars.

RECEPTACLES: A device in which users insert a secondary object in order to activate or control a process, such as a mail slot, coin slot, magnetic card slot, key hole, or garbage can opening.

SAGITTAL: In the direction or location from front to back in the median plane or in a plane parallel to the median.

TRANSVERSE: Lying or being across or in a cross direction.

*U.S. Government Printing Office: 1995 — 392-125