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THE APPLICATION OF ERGONOMICS TO THE DESIGN OF WHEELCHAIRS

by

TERRY CUNNIFFE, Dip. A.D., M.Sc.

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of the Loughborough University of Technology

August, 1974

Supervisor:  PROFESSOR N.S. KIRK, Ph.D.

Department of Ergonomics and Cybernetics

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CONTAINS PULLOUTS
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Hille International Ltd.
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Note on units of measurement used

In the section concerned with the project wheelchair, Imperial units have been used. This system was used for two reasons: firstly, the vast majority of literature associated with wheelchairs and wheelchair research uses this system, and secondly, the machinery on which much of the prototypes were to be built was graduated in Imperial units.

In the section dealing with the development of the body support system, no such constraints were present as the system was fabricated by hand, with the sole exception of the cushions. Therefore, for this part of the work, use has been made of the metric system.
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INTRODUCTION

A wheelchair is primarily a device for providing an individual with mobility when independent locomotion is either impossible or extremely difficult. This mobility is virtually always provided in conjunction with a seated position. There are very many problems associated with wheelchair design, and some of them are the result of insufficient attention being paid to the many functions the wheelchair must perform, and the areas in which these functions are carried out.

The wheelchair is a particularly complicated assistive device: it must be capable of mass production, yet include sufficient adaptability to fit closely a very wide variety of individuals. The option must also be kept open for those individuals who will need individual attention. It must also be regarded as both a static supportive device as well as a dynamic mobility aid. It must relate to the environment in which it is to be used.

Many people from many backgrounds have become involved in wheelchair design, but basically three professions have been particularly concerned: the medical profession, engineers and industrial designers, and very often they have worked exclusively rather than inclusively of each other. In these designs, and these include most current wheelchairs, two factors have been conspicuously absent: firstly, the collection and use of relevant anthropometric and physiological data, and secondly, test programmes to evaluate the design.
It is the premise of this thesis that the most satisfactory design of wheelchairs will come only from the amalgamation of many skills, professions and interests, and that even so, the priorities of the different contributors to this team must be carefully established and a balance drawn between them. Some factors are absolute essentials, others the product of compromise, and yet others determined by quite arbitrary decisions.

The purpose of this thesis is to show a design process in action, illustrating the role of the ergonomist in this process. It has been suggested (First International Biomedical Engineering Workshop Series 2, 1972) that there are fifteen stages in the development of a piece of medical equipment, as follows:

1. Goal setting and concept development. Identification of the clinical problem, its significance in medical, social and economic terms, and its definition on the basis of collaborative effort between the patient and the medical, engineering, and other relevant disciplines.

2. Economic and commercial potential. Home and overseas market assessment, development contracts, priorities based on cost/effectiveness. Initiation of eventual involvement of industry.


5. Prototype development and construction.

6. Prototype evaluation. Function, performance, safety and clinical acceptability, and possible redesign and
specification amendment.

7. Decision on whether further development should proceed and/or whether performance specification should be more realistic. If the findings are affirmative, it is essential that industry become involved.

8. Production specification. Value analysis, design and production engineering, development, production, and customer cost limits.


10. Production assessment and approval.


15. New concepts and actions based on experience and a repeat of the entire design development.

The present thesis covers the first six of these stages, and within these the part played by the ergonomist falls into two distinct parts: firstly, the collection and analysis of all relevant data, and the translation of these data into a form usable by the designer, and secondly, the construction and application of evaluation programmes.

If the situation had allowed the process to continue on to the remaining nine stages, it is envisaged that the ergonomist would have had a role to play, but in a diminishing degree.
It cannot be sufficiently stressed, however, that the outcome of this project has been the result of close and continued co-operation between the ergonomist and the other professions and skills represented, and that this thesis gives in detail only the ergonomist's contribution.
SECTION 1 PREAMBLE

This section is concerned with the basic data on which a wheelchair design must be based. These data are in terms of the user, the personal and social consequences resulting from his need to use a wheelchair, his preferences and present uses of a wheelchair, his medical requirements as presented by clinicians. Anatomical and physiological considerations will be discussed in Section 2, as they relate to specific parts of the wheelchair.

It is recognised that not all these data are scientifically based, and that even those which are experimentally based are not always in agreement, but it was considered important to state them all so that design decisions can be made in the light of all known relevant experience. Where specific data on disabled wheelchair users was totally lacking, it was decided to use data from other sources, where it might reasonably be supposed that the experience was transferable.
1. Personal and Social Consequences of loss of mobility

1.1. Introduction

Failure to achieve independent locomotion, or loss of it, is a serious handicap, but in modern society not necessarily of itself fatal: that is to say that independent locomotion is not now a prerequisite of life. It is however one of the critical factors controlling the quality of life, and some discussion on what this loss may entail is considered necessary.

In terms of the effect on the quality of life, many conditions which result in functional impairment will produce results which, although different in detail, will have much in common, and so for the purposes of this discussion, examples referring to blindness for instance will have as much validity as those referring specifically to loss of independent locomotion.

1.2. Physical manifestations

Manifestations of functional impairment have been classified as follows: Fig. 1 (First International Biomedical Engineering Workshop Series 2, 1972). These manifestations can be modified by several factors: their persistence, extensiveness, progression, the effect and duration of immobility and inactivity, the age, social state, medical and/or physical treatment, general health and environment of the person involved. The modifying factors may make the disability more or less severe.
MANIFESTATIONS

SENSORY
Loss or significant impairment in:
- Sight
- Hearing
- Sensation or feeling in body parts
- Equilibrium

BRAIN FUNCTION
Altered or impaired:
- Orientation
- Speech formation
- Difficulty in initiating or controlling movement
- Involuntary movements, tremor
- Rigidity

SPINAL CORD FUNCTION AND/OR BRAIN
- Jerky movements
- Spasms, spasticity
- Loss of dexterity and accuracy in skilled hand, arm or finger movements
- Involuntary twitching

MOTOR ACTIONS
- Paresis (incomplete motor paralysis)
- Incoordination or clumsiness
- Muscular weakness
- Decreased endurance in walking, climbing or changing position
- Poor balance and posture during movement

MUSCULAR AND MUSCULOSKELETAL FUNCTION
- Paralysis
- Loss of movement and/or feeling
- Muscular pain (often combined with vascular insufficiency)

ANATOMICAL DEFECTS
- Unusual wasting or asymmetrical enlargement of muscle bulk
- Spina bifida
- Defective anatomy
- Cleft palate
- Club foot etc.
- Severe scars and deformities
- Old fractures with bad bone alignment
- Abnormal positioning of body segments (deformity)
- Limited range of mobility of body members

Fig. 1. Relationship between manifestations and deficits
1.3. Effects of disability

The effects of the resulting disability on the life of the individual concerned can be listed as follows: (based on First International Biomedical Engineering Workshop Series 2, 1972)

a) Loss of personal physical independence, requiring full, partial or occasional assistance from others. At one end of this spectrum is a totally helpless bedfast individual, and at the other a fully independent individual who needs assistance only in rare circumstances.

b) Restricted physical mobility: while this is certainly due in the main to the disability itself, it is equally certainly reinforced by the environment in terms of architectural barriers, and also by the design of some of the support equipment used by the individual.

c) Limited or reduced social mobility: social mobility is mainly a product of education and/or job status, and both of these may be severely affected.

d) Decreased health status: decreased range of physiological functions, decreased sensory input from restriction of activities of daily living, decreased physical activity, medical complications and resultants, poor physical work capacity.

e) Behavioural disturbances: these may occur over a period of time from the onset of disability. They are:
- impaired concentration
- depression, mourning and dependency reactions
- excessively demanding behaviour
- unco-operative attitudes or withdrawal
- unrealistic expectations
- decreased personal choice of activities
- loss of work adjustment and habits
- loss of work tolerance

These effects, singly or in combination, will in some measure determine the disabled individual's quality of life, but there is one other extremely important factor which must be considered, and that is the attitude of society towards him.

Social attitudes

While it is extremely difficult to pinpoint reasons for society's often unfavourable attitude towards the disabled, the following theory is presented as offering at least a partial explanation of the roots of this prejudice. A man's value to his group could be measured in two ways: firstly his physical contribution to the economic survival of that group, and secondly his ability to produce offspring to augment and eventually replace him. Exceptions could only be tolerated if the individual could offer exceptional service, for instance of a religious nature.

A disabled individual was thus at a double disadvantage: he might be an economic burden to the group, and he might be actively discouraged from reproducing for fear that his offspring would inherit his disability, or perhaps, failing that, would
need to be supported by others during their childhood. Another factor is also possible, that of fear of contagion, further reducing the viability of the group. It seems likely that these three factors, all relating to the group's survival, form the basis of present-day prejudice. Interestingly, even today a legal difference in terms of provision is made between war disabled and civilian disabled.

The following definition of society's attitudes towards the disabled is taken from Goffman (1963). "Given the fact that normals in many situations extend a stigmatized person the courtesy of treating his defect as if it were of no concern, and that the stigmatized is likely to feel that underneath it all he is a normal human being like anyone else, the stigmatized can be expected to allow himself sometimes to be taken in, and to believe that he is more accepted than he is. He will then attempt to participate socially in areas of contact which others feel are not his proper place. Thus a blind writer describes the consternation he caused in a hotel barber shop:

'The shop was hushed and solemn as I was ushered in and I was vitually lifted by the uniformed attendant into the chair. I tried a joke, the usual thing about getting a haircut once every three months even if I didn't need it. It was a mistake. The silence told me that I wasn't a man who should make jokes, not even good ones'.

....The general formula is apparent. The stigmatized individual is asked to act so as to imply neither that his burden is heavy, nor that the bearing of it has made him different from us; at the same time he must keep himself at that remove from us which ensures our painlessly being able to confirm this belief about him. Put differently, he is advised to reciprocate naturally
with an acceptance of himself and us, an acceptance of him that we have not quite extended him in the first place".

This attitude of society that a disabled individual should 'know his place', that he is only partially acceptable, and then under certain conditions, is gradually changing. It is possible that this is because the need to reproduce the species is no longer urgent - quite the opposite in fact - and much recent social legislation would tend to support this belief: present laws on abortion, contraception, homosexuality, suicide and divorce can be viewed in the same light.

There is still a very long way to go in achieving full social acceptance of the disabled at all levels, and so society's attitude has a profound effect on the quality of a disabled person's life. This effect is probably in direct proportion to the degree of dependence imposed by the disability, and there is no facet of his life that is untouched.

1.5. Equipment

Where functional impairment exists, there has been an increasing endeavour to provide equipment which is a replacement or a substitute or assistance for the defective part. The rejection of this equipment can be a distinct problem for those working with the disabled (BMA Planning Report No 2, 1969), and has two probable sources: firstly, the unwillingness of the individual to recognize his handicap, or secondly, fear that the equipment may make him less socially acceptable. There is, of course, also the possibility that the equipment is at fault.
For a device to be personally acceptable to the user, the following axioms need to be observed (First International Biomedical Engineering Workshop Series 2, 1972)

1. A device must preserve the dignity of the individual.
2. When in normal use, the device must not make intellectual demands on the person (unconscious level operation).
3. The device must not make the user conspicuous but some instant recognition factor may be desirable, e.g. white cane.
4. If the device is obvious it must be of good design, style and fashion.
5. There must be no nuisance factors such as noise, smell, leaks etc.
6. The device must be reliable, failsafe and quickly and easily maintained and serviced.
7. Similarly, the user must have confidence in the technical ability of the device to perform properly.
8. The device must not be unreasonably restrictive, i.e. functional gain must exceed functional cost.
9. It should be comfortable and body-compatible.

For a device to be totally socially acceptable, it is probably true to say that it must be either utterly unobtrusive, or in such common use as to cause no comment.

1.5.1. Mobility aids: the wheelchair

Apart from walking sticks, the wheelchair is the most frequently used mobility aid (Harris, 1971), and performs an extremely
important function in the life of a person who is not otherwise independently mobile. However, it does by its design impose certain limitations, and in the present state of wheelchair design, not all these limitations are capable of a solution. It is considered important to state them in spite of this, against the time when the design of mobility aids can produce solutions.

Some of the limitations are obvious: a wheelchair physically cannot replace the function of legs. Some attempts have been made to produce stair-climbing chairs, but many factors, including size, weight, power source, economics and so on make it most unlikely that these will come into common use. Wheelchairs will not adapt to many different ground surfaces and gradients; sand, gravel and cobbles defeat most, and gradients present problems of stability and energy expenditure. A person in a wheelchair takes up more space than a person walking, and will thus find certain areas inaccessible. A wheelchair also places restrictions on how far a person can reach, on how much of his environment is immediately accessible. "...... housewives in wheelchairs tend to be 'non-active', 34% of them not being able to do most of their household chores. Although the numbers are small, the data do show that women housewives who use wheelchairs are less likely to be able to do their chores than other women housewives. Even though the proportion of women housewives using wheelchairs who cannot do their own chores does vary with the degree of handicap, what seems to have an even more limiting effect is simply being in a wheelchair". (Harris, 1971)
Other limitations concern social behaviour: custom demands a standing posture as a mark of respect, and sometimes as an assertion of authority, and these behaviour patterns are denied the wheelchair-bound individual. The effects of the loss of these patterns have not been investigated, but at the very least, a certain differentness must be noticeable.

Finally, it seems possible that the provision of a wheelchair offering other than an upright sitting posture may have unexpected side-effects. Posture, orientation and distance offer important clues about attitude (Mehrabian, 1968a), and by providing a backward-leaning posture, a wheelchair can predetermine judgments about the attitude of the person in the wheelchair. "...regardless of the sex of the communicator or addressee, backward lean, which was a parabolic function of attitude, attained a maximum for moderately disliked addressees and diminished sharply for liked and intensely liked addresses". (Mehrabian, 1968b) This would tend to indicate that a person in a semi-reclining wheelchair gives the impression of disliking those to whom he is speaking, although the extent to which postural, as opposed to facial or verbal, clues are used in making judgments of attitude is not known.

1.6. Conclusion

To sum up, loss of mobility has a profound effect on the quality of a person's life in three major areas: on the person as an individual, on the person as a member of society, and finally in terms of the equipment provided to compensate for his loss of mobility.
CHAPTER 2

2. Characteristic uses of the wheelchair

2.1. The characteristics of wheelchair users need careful consideration before a wheelchair is designed, and this for a variety of reasons. Firstly, the more closely a wheelchair conforms to the requirements of the user, the greater the use of it will be, with a corresponding increase in mobility. Secondly, fewer adaptations and additions will be needed - these tend to make the use of the chair more complicated. Thirdly, the wheelchair is unique in the field of aids and appliances because of the number of roles it has to perform, and the relative weighting of these roles by the user will certainly have a bearing on the design.

There are however great problems in establishing the users' requirements, as these will obviously differ according to the age, physical condition, activities and so on of the user. Also, judgments by users will be affected by their present chair, and it is often difficult to suggest improvements in the abstract. Furthermore, when a wheelchair fails to live up to the user's expectations, it is not always a simple matter to decide why: if for instance the user cannot transfer from his wheelchair to the lavatory, is it the wheelchair - for instance the footrest gets in the way - , the architecture, or the physical condition of the user that is causing the major difficulty? There is also the possibility that the user's demands may be mutually incompatible, so that compromises need to be made: for example lightness of weight may need to be balanced against ruggedness, sitting comfort against foldability and so on.
In spite of these difficulties, there has been one major attempt to establish the characteristics and requirements of wheelchair users: between 1966 and 1968 two surveys were conducted by members of the Department of Ergonomics and Cybernetics at Loughborough University of Technology, one a postal survey resulting in 448 usable returns, and the other an interview survey of 10% of those who answered the postal survey. The subjects were all wheelchair users residing in the county of Leicestershire. The summary of the findings is quoted below. (Platts, 1971)

2.2. Summary of users' characteristics

1. The majority of wheelchair users were adults. About half were aged over 55 years, only a small proportion were aged between 20-40 years, and the smallest group were young adults or children.

2. Wheelchair users were predominantly women. The greater proportion of women to men was significantly different from the equal proportion in the census.

3. Proportionately more of the women than the men were older than 50 years.

4. The illness leading to the disablement tended to start in the main ten years before the survey, and most frequently between the ages of 30-60 years.

5. Between a half and two thirds of the users were dependent on wheelchairs for mobility in the home and were therefore considered to be "wheelchair bound". The remainder were considered to be "semi-ambulant".
6. The wheelchair bound required wheelchairs for use inside the home as well as outside, whereas the semi-ambulant needed wheelchairs primarily for use outside.

7. Use of wheelchairs inside the home started most frequently in adulthood and in particular at ages over 40 years.

8. For those who used a wheelchair inside the home, the number who had used one for up to five years approximately equalled the number who had employed one for more than five years.

9. There appeared to be a tendency for use outside the home to start at a slightly younger age than use inside the home. Outside use also started most frequently in adulthood but predominantly at ages over 30 years.

10. Wheelchairs had been used outside for more than five years more frequently than they had been used for less than five years.

11. A minority of the wheelchair bound group could walk to a limited extent or move around by other means, inside the home.

12. All the semi-ambulant group walked around inside the home and the majority of this group could walk, at least a few steps, outside the home.

13. About half of the wheelchair users could stand but only for a short time, though generally at least long enough to transfer.

14. Only a few users could stand or walk without support of some kind. Most used sticks, crutches, another person, or furniture as support. Some also wore calipers.
15. Transfer to and from wheelchairs was effected most frequently by standing. Transfer was also achieved by a manoeuvre over the side of the wheelchair, or in a few instances by carrying or hoisting.

16. A majority of the users could operate wheelchair brakes. The poor position of the brake levers and the unreliability of the brakes were criticised.

17. For those using wheelchairs in the home, there were about two users who self propelled to one who was pushed. Only a minority said they could propel themselves outside, or were able to negotiate a step or kerb without assistance.

18. Self propulsion was most frequently effected by pushing the handrims, or handrims and tyres. Current handrims were criticised for being easily damaged, difficult to grip, and located too close to the wheels.

19. Some of the users with paralysis on one side used two handrims mounted on the same wheel but others used one handrim and their feet because it was an easier technique to master. Another small group used only their feet for propulsion.

20. About 40% of the users said they tended to have spasms or tremors, but relatively few said these affected their ability to control wheelchairs, or to stay in them.

21. About a third of the users were incontinent to some extent and 27% were severely so.

22. The majority said they did not suffer from sores, but about 20% did.

23. A minority had postures requiring special support or
shaped seats.

24. There appeared to be a tendency for disability to become worse with time. However many users had remained in the same condition and a few said they had improved in the two year period between surveys.

25. In addition to the progressive effects of disability, all the natural effects of ageing were apparent in the elderly users.

26. The majority of users did not drive a vehicle, could not fold current wheelchairs, nor lift them into a vehicle.

2.3. Summary of characteristic uses of the wheelchair

1. Wheelchairs are used in three different environments, viz: inside the home, outside the home, and at places of employment.

2. Wheelchairs were used inside by about 60% of the sample. The intensity and variety of use was greatest inside the home.

3. Almost all of the sample used wheelchairs outside but only a small minority used one at work.

4. Wheelchairs were most frequently used daily. In particular, all who used wheelchairs inside their homes did so daily. However those who needed wheelchairs only outside tended not to use them daily (in the proportion of about two who did not to one who did).

5. Inside wheelchair users tended to be in wheelchairs for longer periods of time than those using them only
outside. A majority of indoor users used wheelchairs for over 6 hours each day.

6. About half of inside users tended to stay in one room and moved between rooms only infrequently. The remainder were more active but only 20% moved freely between rooms.

7. Mobility about the home was limited by three main factors, viz:

   Obstacles such as limited space narrow doorways and floors at different levels with steps between.

   The manoeuvrability of the wheelchair and its size.

   The effects of the disability, both on physical capacity and mental attitude.

8. Inside the home wheelchairs were used over high friction surfaces, such as carpets, and relatively smooth ones, such as linoleum.

9. Outside, wheelchairs were used mainly to move from place to place over relatively short distances and to go to public places such as shops, or places of entertainment.

10. Wheelchairs were used over a wide range of surfaces outside the home. These varied with respect to inherent differences in friction, such as between grass and pavement, as well as changes due to weather conditions. In addition slopes and kerbs were encountered.

11. At least half of the users found wheelchairs to have uncomfortable seats. Factors contributing to this discomfort included the lack of upholstery, the lack of ventilation of the leather cloth, the tendency of
the seat to sag or tear under heavy users, and the
length of time some users had to spend in their wheel-
chairs. Additional features, such as headrests and
lumbar supports, were required to facilitate comfort.

12. Wheelchairs were used with a variety of household
furniture and fittings. Differences in height between
wheelchairs and items of furniture caused problems for
use together, and for transfer from one to the other.
The fixed height of wheelchairs caused problems for
those undertaking housework or jobs which had to be
done at different levels. The shape and manoeuvrability
of wheelchairs caused problems with respect to approach-
ing close to furniture.

13. Wheelchairs were used to carry a variety of objects.
The main types of items mentioned were, walking aids,
trays as carrying surfaces, personal belongings, and
shopping.

14. Wheelchairs were used to ferry the user between their
homes and cars. Wheelchairs were also taken in cars
for use at the end of journeys.

15. In addition to being carried in a car or taxi, wheelchairs
were taken in the following types of public transport:
trains, ambulances, buses, ships and aeroplanes.

16. Only a minority of wheelchair users were employed. At
places of employment the wheelchair was used for mobility,
both into the building and around the office or factory.
It was also used as the work seat.
2.4. Summary of uses by an attendant

1. When assisting patients in wheelchairs, attendants' actions had to be tailored to the limitations imposed by the wheelchairs.

2. Attendants were an important aid to transfer. Their assistance involved supporting, sometimes completely, the user, as well as manoeuvring users and wheelchairs into new positions, frequently in a limited space such as in a toilet.

3. Attendants were frequently required to lift the patient out of wheelchairs or onto their feet.

4. Attendants were a major source of power for moving wheelchairs. The main problems with respect to pushing were, the effort required, the difficulties of manoeuvring a heavy load on slopes, over kerbs, and over rough ground. Aids to pushing, such as the pushing handles and tipping bars were criticised for their unsuitable location, size and shape.

5. Attendants as well as users were operators of control mechanisms, such as brake levers, and ancillary components, such as foot rests.

6. Activities such as folding and lifting empty wheelchairs were performed more frequently by attendants than wheelchair occupants.

(Platts, 1971)
CHAPTER 3

Medical Requirements

3.1. Introduction

There are very many pathological conditions which necessitate the provision of a wheelchair, and as far as their implications for design are concerned, it is considered that no useful purpose is served by listing these causes by name. This is because the results of a given disease or disability vary widely between individuals, and also because although endemic or epidemic disease may vary greatly from country to country, they may well result in common needs in terms of wheelchair design. However, it is also true to state that medical practitioners do not always agree on the different aspects of wheelchair design, and it is possible that this disagreement arises out of uncertainty as to the precise medical role of the wheelchair.

Some doctors consider that the primary function of the wheelchair is to offer mobility: "The ability to move from place to place, even if it is within the confines of one room, may make all the difference between some degree of independence and complete dependence with the frustration which this entails. Wheelchairs are therefore as important to many disabled patients as artificial limbs are to amputees. The same care in selection and training in manipulation is necessary for both types of equipment". (Nichols, 1971)

For others, different considerations come first. For instance: "The comfort of the patient must be given first consideration
for if he cannot use the wheelchair with some degree of comfort it will be of little or no use". (Deaver, 1949) Or: "The wheelchair prescription should not limit itself to locomotion, safety and comfort, but should reflect consideration of the individual's ability to cope with cultural and home environment, and vocational and avocational activity". (Lee, Pezenik and Dasco, 1967)

In general, the medical profession is recommended to prescribe a wheelchair which offers "maximal comfort, safety, manoeuvrability and independence" (Lowman and Rusk, 1961), but occasionally further considerations are mentioned: "...the physician should be aware of 1) the diagnosis, disability, prognosis and life expectancy of the patient 2) whether the chair will aid or hinder him in performing the activities of daily living 3) the physical setup of the home or area where he will be using the chair most frequently, and 4) his financial resources". (Lowman and Rusk, 1960)

In many instances, clinicians writing about the prescription of wheelchairs will continue with details of existing wheelchairs, dimensions, accessories and so on, and advise what type of patient will fit what type of chair. Here, however, differences of opinion arise, and sometimes flat contradiction. For instance:

Armrests: For amputees, not detachable arms (Fowles, 1959)
For amputees, detachable armrests, giving 1½" extra seat width for prostheses recommended (Lowman and Rusk, 1961)
Removable armrests for all who cannot stand, except for bilateral amputees (Lee et al. 1967)
Cushions: "For spinal cord injury...4" polyurethane foam rubber cushion with woven cloth cover, not heavy gauge plastic" (Spiegler and Goldberg, 1969) For quadriplegics, 3" to 6" foam rubber cushion, covered with washable plastic (Fowles, 1959)

Seat/back angle: "The seat is 5° from the horizontal...and the back 15° from the vertical". (Kamenetz, 1969)
"Too great a recline may make the patient slide in the seat and be a cause of inability to propel the chair...A 5° tilt is usually the most comfortable" (Nichols, 1966)

Backrest height: "Upholstery should generally end below the scapula". (Spiegler and Goldberg, 1969)
"For comfort, support and good sitting posture, the back should extend up to approximately 2" above the inferior angle of the scapula". (Hoberman et al., 1953)

Seats: " (a) A British study states that a hammock seat spreads weight over the entire gluteal area producing anesthesia of the skin and poor posture. Therefore, the solid seat was recommended.
(b) The Case Institute of Technology study indicates that the more pressure kept off the ischial tuberosities and distributed to the buttocks and thighs, the less likelihood of breakdown of the tuberosities from sitting. This is a serious problem for persons who lack sensation."
(c) Other studies point out that the ischial tuberosities are equipped to bear weight and that the rest of the flesh is not. One study argues against the contour seat because the joints of the hip are thrown out of alignment if weight is carried in that area". (Bergstrom, 1965)

No evidence has been found that the medical profession required a wheelchair as a physical therapeutic aid, for instance to correct postural deformities or to improve respiratory function, although sitting as opposed to lying down can be beneficial in preventing or diminishing some of the pathological consequences of immobility such as decalcification and kidney stones, or in conditions where dyspnea and pulmonary congestion are threatening or present (Levine, quoted by Kamenetz, 1969). However, this does not apply specifically to wheelchairs, and does not mean that the patient should necessarily be mobile. At best, doctors expect a wheelchair to preserve the patients' physical status quo, and not add to their difficulties by creating further problems.

Here there are three main areas of concern: accidents, poor posture, and problems of pressure, all of which have been the specific result of using a wheelchair.

To sum up, it is not possible to use as design criteria the causes of disease or disability as there is little common ground: on the positive aspects of wheelchair use there is
little agreement within the medical profession on the overall concept now in the detail design. There is agreement, however, on the negative aspect: that a wheelchair should have no deleterious effect on its occupant.

3.2. Problems with medical sequelae

3.2.1. Accidents

According to Kamenetz (1971), the six most frequent types of accidents involving wheelchairs are as follows:

1. Failing brake: this can cause the user to fall during transfer or when sitting or rising.

2. Tipping footrest: the wheelchair tips forward when the user steps on the footrests as he sits down or gets out.

3. The slide: the user slides out of his wheelchair. This accident occurs most frequently to users who are too weak to adjust their position, and to those who are unaware of their posture because of sensory deficiency.

4. The forward dip: the wheelchair tips forward when the user's weight is shifted too far forward. This is caused by an alteration in the centre of gravity.

5. The backward toppling: the user tips over backwards when he leans back and jerks the chair while attempting to cross a threshold or other obstacle. Although this accident occurs most often to patients who have strong arms and shoulders, it sometimes happens to those who have had leg amputations that result in a shift in the centre of gravity.

6. The caught foot: the user's foot becomes caught under the footplate or behind the legrest, usually because
of muscle spasm, paralysis, or lack of sensation in the leg.

Accidents also occur because of the design of the chair (legs being caught on projections during transfer), and because of the difficulty of providing materials capable of withstanding constant use without degradation. (Platts, 1971)

Very often, the medical professions solutions to the question of accidents is twofold: firstly, adequate training of the user in the use and maintenance of the wheelchair to instil safety habits, and secondly the use of restraints: toe straps, heel loops (Lowman and Rusk, 1960), leg straps, seat belts (Kamenetz, 1969), shoulder harness (Barbato, 1958) and head restraints (Kottke, 1965) are frequently recommended.

Thus it appears that there are three main causes of accidents in wheelchairs: shift in the centre of gravity, lack of restraint, and unreliability of parts. To prevent the first, training is essential, for while the chair can be made as stable as possible at rest, the situation alters dramatically with motion. As an example of the problem, it is quite possible to fall out of the same wheelchair both forwards and backwards in different situations. (Roberts, personal communication) For restraints, it seems reasonable for the medical profession to expect a wheelchair under normal circumstances to accommodate in its design for certain generally observed problems such as leg spasm. In certain circumstances, for instance in extensor spasms, other restraints may be needed. Finally, there is a duty on the part
of the manufacturer to ensure the highest possible standard of all parts of the wheelchair to prevent failure, as well as a knowledge of methods of use on the part of the designer so that sharp projections and so forth are avoided, and there is also a responsibility on the part of the user to maintain the chair to a safe degree.

3.2.2. Posture

The difficulty of maintaining a good posture in a wheelchair is the second cause of concern. "After a patient has been in a wheelchair for two or three years, he often begins to slouch". (Edberg, 1965) However, while many sources agree on the necessity for good alignment (Fowles, 1959, Mundale, 1965), there is little agreement in detail as to what this means. It is probably fair to say that the disagreements are at least in part due to the impossibility of making recommendations which can be applied to all wheelchair users: the needs are as varied as the physical conditions of the users, and attempts at overall recommendations will be at best only partially successful.

Particular postural problems which will need consideration are as follows:

1. Muscle weakness such that full support is needed.
2. Collapsing scoliosis
3. Flexor spasms, particularly of the legs.
4. Flexion deformities.
5. Extensor spasms.
6. Ankylosis.

Pulmonary ventilation, digestion and venous return from the
legs may also need to be considered.

These problems may need to be looked at on an individual basis, but some considerations may be incorporated into the basic design. For instance, footrests may be designed with flexor spasms in mind; the legrest may be elevating to encourage venous return and to prevent contractures; the possibility of a reclining backrest may be considered, together with a headrest. It is obvious that no single wheelchair can accommodate for all possible requirements, so in designing a wheelchair it is necessary to choose which sets of conditions to cater for, and to make a fine balance between adaptability and cost.

In providing support on an individual basis for particular postural problems, the following statement needs considering:
"It is usual to find that the more complex the cushioning, the less likely it is to be successful. Although it is often necessary to adjust the sitting-space to the patient, the cushioning provided for the purpose must be simple, repeatable, easily removable and replaceable and not restrict the patient. Otherwise it will be neither acceptable nor comfortable".
(Nichols, 1971)

3.2.3. Pressure

In able-bodied human beings, the pressure tolerance of tissues is rarely exceeded, since the discomfort involved initiates movement to remove pressure from the affected area. The reason for the discomfort is the fact that the capillaries become compressed, and this leads to local ischemia. When the pressure
is relieved, there is an increased flow of blood to the area; this process is called reactive hyperemia. It is possible that anoxemia, the reduction of the oxygen content of the blood, is responsible for this. (Kosiak, 1961) Normal capillary pressure has been found to vary between 40 mm Hg on the arterial side, and 10 mm Hg on the venous side (Weinstein and Davidson, 1966), but no figures have been found which relate specifically to capillary pressure in the weight-bearing areas. In animal studies, Kosiak (1961) found that varying pressures of up to 190 mm Hg for a period of one hour did not produce any noticeable microscopic changes in tissue, whereas pressure of 70 mm Hg did produce changes after two hours. Thus there is a time/pressure relationship in the creation of destructive tissue changes. But as well as compression force, shear force has also been shown to play a very significant part in this destruction. (Reichel, 1958)

Not all wheelchair users will be susceptible to damage in this way: the most vulnerable are those who, because of loss of sensation, have no warning that damage is occurring, and those who, although aware of discomfort, are unable, because of insufficient strength, to change their position. There are other predisposing factors, such as lack of padding over bony prominences, poor general health, poor local blood circulation, mental confusion, incontinence and excessive sweating, but in the last two, a distinction must be made between sores caused by skin maceration, and pressure sores, which may not be visible on the skin for up to 48 hours after the damage has occurred. (Norton, 1964)
It was long thought that decubitus ulcers were an inevitable concomitant of spinal cord injury due to interference with 'trophic nerves', but "paraplegia has been shown to have no specific effect. Ulcers occur in this condition from a combination of causes: immobility due to motor paralysis, and absence of the normal painful stimuli from the skin and deep structures which are responsible for the frequent postural changes performed unconsciously by normal people, awake or asleep". (Bliss, 1964)

The incidence of decubitus ulcers is not known, but in paraplegics it has been reported variously from 25% to 75%. (Nichols, 1971) Superficial ulcers have a relatively good prognosis, but deep, perhaps gangrenous ulcers may take months to heal, and when healed, may leave an area of scar tissue extremely susceptible to further breakdown.

The severity of the problem is underlined by the number of preventive and curative practices that have been advocated. Bliss et al. (1964) have listed the following:

"Other investigators have described the results of fortifying patients with extra proteins, vitamins, anabolic hormones, insulin and antibiotics, protecting the intact skin with ether, alcohol, soap, silicone, various creams, sticking plaster and photographer's rubber cement. Sores themselves have been treated with chlorophyll, brine, sugar, enzymes, jam, vitamin E, dried plasma, honey, antibiotics, tannin acid, oxygen, Marmite, ultra-violet light, sunlight, electric light, plastic sprays, and the juice of a South American plant (Centella asiatica). Some surgeons have cut away the sloughs, others retained them
as long as possible.... Patients have been nursed on plaster beds, air beds, water beds, sawdust beds, sheepskins, mats of rubber spikes and sorbo and plastic foam. They have been massaged, ventilated, strapped in machines which turn them completely over, tipped from side to side, or nursed on mattresses which vary the supporting points underneath them. They have been immersed in water, suspended in hammocks and by wires passed through the iliac crests and clavicles. They have had their bony prominences removed. Good results have been claimed for all these measures, but, as other writers have observed, their multiplicity alone seems to suggest how incompletely successful any one of them is". One may be forgiven for thinking that it does not matter so much what one does, as long as one does something.

For wheelchair users liable to pressure sores, there are two main areas where damage may occur: firstly, under and around the ischial tuberosities, by compression force, and secondly, around the sacrum, by shear force due to sliding down in the chair. The compression forces under the buttocks have been measured by various means by various researchers such as Lindan et al. (1965), Kosiak et al. (1958) and Houle, (1969). However, it is difficult to draw general conclusions about the amount of compression force found in these studies, as some factor is missing in each one: for example, the length and width of the seat; specific anatomical measurements of the sitting area; the height or angle of the backrest; the foot support and its relation to leg length; the compressibility of the seat
surface when cushions were used, and so on.

In another study, Mooney et al. (1971) made an evaluation of the pressure distribution qualities of ten commercially available seat cushions, all designed to distribute pressure. Their findings were as follows:

1. There was no correlation between the subject's weight and pressure distribution.
2. No cushion presented was ideal, or able to reduce pressure to the skin below arterial capillary level.

They continue: "The surprising finding of this study was the failure of the fluid-filled cushions to achieve their hypothetical ideal of total, even pressure distribution. It seemed logical that if the supporting medium could flow, it would distribute pressure evenly throughout the supporting medium, according to the laws of fluid dynamics. The reason for this failure was the surface tension of the enveloping membrane. Even though the fluid can distribute pressure evenly, the container is limited by its physical qualities and elastic limits". Also mentioned is the difficulty encountered by patients trying to maintain stability against a floating reaction point. The final recommendation is: "The experimental design of resin-impregnated polyurethane foam with a 1" x 8" x 10" cutout area under the ischial tuberosity appears to most closely approximate the clinical criteria for an acceptable wheelchair seat cushion for paralyzed patients". Conversely, Kosiak (1961) states: "Cut-out areas intended to decrease or eliminate pressures over the bony tuberosities only tend to divert more
of the weight bearing to the surrounding area".

Finally, all authorities agree that the only sure prevention of pressure sores is the complete elimination of pressure at frequent intervals, and, if necessary, the protection of the danger areas. It does however seem theoretically possible to produce a mathematical model for a paralyzed but otherwise healthy individual in which skinfold thickness, total available body area for sitting on, distribution of weight due to anatomy and weight are combined to give an accurate idea of the optimum type of seat for that individual.

Shear force can only be prevented by maintaining a good posture in the wheelchair, with particular attention being paid to seat length - too long a seat will encourage a sliding motion - legrest length and seat/back angle.

3.3. Conclusion

The medical requirements of the wheelchair are that it should preserve the patient's physical status quo, and that it should take into account special anatomical or physiological considerations when these present problems.
SECTION 2  PREAMBLE

This section is concerned with the wheelchair per se, its constituent parts and their functions, and how they relate to the user. It is divided into two parts, the first part dealing with the wheelchair as a static device, and the second part dealing with the wheelchair as a dynamic device.
CHAPTER 4

The wheelchair as a static device

4.1. Introduction

In order to take advantage of existing recommendations and research associated with wheelchair design, and to relate them to the projected concept of a new wheelchair, it is necessary to examine the function of wheelchairs and their constituent parts, and equate these functions with the requirements and recommendations which pertain.

4.2. The wheelchair, its parts and their functions

Within the present distribution of wheelchairs in Great Britain, there exist three main types of wheelchair:

i. manually propelled

ii. attendant propelled

iii. motorized

Within each category, there are derivatives designed to accommodate for the specific requirements of like groups of disabled users.

Although differences exist between these three categories of wheelchairs in terms of motive power, enough basic similarities are present for many of their aspects to be discussed jointly, especially as many wheelchairs available for prescription can be adapted to perform any of the roles.

4.3. The wheelchair seat

In the support of the user within a wheelchair, the seat is the reference plane from which the relationship of the other
supporting areas is made. Depending on the role of the wheelchair and the characteristics of its users, the height of the wheelchair seat in relation to the floor may vary. The variation in seat height can be due to a number of factors including:

1. method of propulsion
2. supplementary cushioning or body support system
3. environmental considerations
4. anthropometry

Discussion of these factors will be made as they apply to specific areas of concern.

As a supporting surface, the wheelchair seat must provide for a number of requirements if it is to satisfy the demands of both its user and the prescribing clinician. These requirements can be listed as those relating to size, shape and comfort, and are discussed as follows.

4.3.1. Size

If the wheelchair seat is used in conjunction with the footrests, the supported body configuration of the user can, if no skeletal deformation exists, be equated in many respects with that of the able population, although factors such as loss of sensation and extended sitting periods will need consideration. In respect of seat dimensions, these considerations will be in the achievement of a closer correlation between the user and the seat than would be necessary or provided for the 5th to 95th percentile range of the able population. This need for closer correlation or better fit of wheelchair seat to its user is maintained for reasons of
armrest proximity in the width, and backrest location in the depth.

4.3.1.1. Seat width

With regard to seat width, a number of controls are exercised on this, such as the overall width of the wheelchair in relation to architectural features such as doorways, but the main consideration is its relation with the armrests. Symmetrical support within a wheelchair is of extreme importance if a good posture is to be maintained. In the maintenance of this posture, seat width is a deciding factor, as the majority of current wheelchairs of the lateral canvas folding type use the seat width to control armrest spacing.

If seat width is considered as a dimension without this association with armrests, its specification will be influenced by its role as a supporting surface. "The functional minimum width is determined by the need for support of the ischial tuberosities; but for body stability, a relation to the trochanteric width appears to give a more realistic estimate". (BS 3044, 1958) Where the association with armrest spacing is maintained, seat width will be that of hip width plus 1" on either side. (Spiegler and Goldberg, 1968)

4.3.1.2. Seat depth

In the consideration of seat depth, two factors must be taken into account, firstly the consequence of providing an excessive seat depth, and secondly that associated with the specification
of a foreshortened seat depth.

1. Where a seat depth is provided that exceeds the user's popliteal/back sacral plane dimension, its effect will be threefold: firstly in the encroachment into the popliteal area, which is undesirable (Spiegler and Goldberg, 1968), secondly in the displacement of the user's trunk so that the emphasis of back support is removed from the desired lumbar region to the thoracic region (BS 3044, 1958), and thirdly, the potentially dangerous forces set up in the user's seat contact area due to the angular loading produced by the back. (Reichel, 1958)

2. The problems that are associated with the provision of too short a seat depth result from lack of trunk stability, and also pressure on the buttocks from contact with the backrest (BS 3044, 1958).

4.3.2. Seat shape

The seat shape, and included in this the seat angle, is paramount in the maintenance and possible improvement of the user's condition. Because of the often extended periods of sitting, and possible sensory loss, the dangers of pressure build-up and its associated ulceration must be accommodated for. Discussion on certain aspects of seating and posture has already taken place in Chapter 2 in relation to ulceration, and estimates made of its prevalence in paraplegic wheelchair users indicate a range of between 25% and 75% of the total.

Accepting that "predisposing factors to the development of
Pressure sores are senility, mental deterioration, confusion, poor general physical condition, unconsciousness, limitation of mobility and incontinence" (Nichols, 1971), the problem remains basically one of pressure distribution. Given normal contact between a constant load and a flat surface, pressure will vary as the area of application of the load, and a considerable reduction in pressure can be achieved by increasing the area of contact. For seated individuals, a reduction in pressure by this means has definite parameters as only part of the seated body area is capable of sustaining weight. "The thighs are anatomically and physiologically unsuited for supporting the weight of the sitting body". (BS 3044, 1958) A concentration of weight around the load bearing ischial tuberosities also produces difficulties as the reduction of the load bearing area increases contact pressure. The inference must be taken that a controlled distribution of pressure around the ischial tuberosities without encroachment into the soft thigh area is desirable.

Studies carried out on normal seated subjects (Swearingen et al., 1962) have shown that although a reduction of seat loading of one third of the body weight can be achieved by the addition and use of footrests, armrests and slightly sloping back, the reduction in loading does not necessarily infer a reduction in seating pressure, and that without provisions for pressure distribution nearly half the body weight is carried on 80% of the sitting area.

Faced with the problem of contact pressure, only one solution is available in terms of its dissipation, and that is to reduce
its concentration by increasing the contact area. The desired reduction can only be achieved by providing for a closer fit between the supporting surface and the sections of the user's body that can anatomically and physiologically support pressure.

The difficulty in providing a contoured surface of adequate proximity is that associated with variations in somatotype and bone display. In offering a solution to this problem of pressure dissipation and seat 'fit', two possibilities exist, firstly, the design of a fixed contour seat, the shape of which will be the product of evaluation, and secondly the provision of adaptable seating which will accommodate to the configuration of the user. Examples of these two approaches are those of a commercially available polypropalene general purpose chair, and polyurethane or foam rubber supplementary cushioning commonly used with slung canvas wheelchairs.

Subjective evaluation studies carried out on contoured polypropalene chairs (Shackel et al., 1969) have shown that for able subjects extended periods of sitting, i.e. 3 1/2 hours, are possible without discomfort in this type of chair, and it is thought that an analysis of the characteristics of fixed contour chairs and foam cushioning offer distinct advantages, and will be discussed later under 4.3.4. Seat upholstery.

4.3.3. Seat angle

As with many other features of wheelchair design, the desirability of an angled seat will be the product of an interrelation
of its provisions with the role the chair is to perform. Two possibilities are realistically available with regard to seat plane position: firstly a configuration which is parallel to the ground, and secondly one that slopes negatively from front to rear. Depending on the role the wheelchair is to adopt, both positions have advantages, and can be considered as follows.

With a level plane seat, studies have shown (Lundervold, 1951 quoted in BS 3044 1958) that muscle activity in the backs of seated individuals is retarded with this configuration and periods of prolonged sitting are judged more comfortable. This advantage must be considered in relation to those offered by the angled seat which has been found to provide for a better anatomical arrangement between trunk and thighs (Keegan, 1953) and a more positive buttock location when used with an angled back (BS 3044, 1958)

With regard to the degree of seat angle, this will be the result of correlation between seat height and anthropometric considerations, but it is generally accepted from seating studies that for the vast majority of individuals an angle of 5° measured from a plane parallel to the floor (i.e. sloping downwards from seat front to back) is acceptable. (Branton, 1966)

4.3.4. Seat upholstery

In determining the type and level of upholstery to be provided in a wheelchair, a judgment must be made between the characteristics of the material and the physical demands made on it by
the projected user. An example of this balance of judgment is
that of the common use of PVC coated fabric in most current
wheelchairs. The desirable characteristics of the material
are those of durability, flexibility and ease of maintenance,
but the quality of these features is diminished by the material's
impermeability and insular properties. With certain types of
disability, notably patients with chronic complete transection
lesions, periods of extensive sweating are often recorded due
to the individual's inability to vasodilate actively to compen-
sate for ambient temperature rise (Wyndham and Guttman, 1955).
Unless provision is made to accommodate for this moisture in
the upholstery of the supporting surface, ulceration of the skin
can occur (Nichols, 1971). Where friction contact is made with
an insular material, static electricity produced by the contact
will attract to the surface particles of dust etc., and the
resultant mix of these particles with the products of excessive
sweating and/or incontinence will constitute a health hazard.

It is necessary therefore in the specification of upholstery
materials to consider the balance of factors such as these, with
the emphasis of choice made to protect the physical condition
of the wheelchair user.

4.3.4.1. The materials of upholstery

It is accepted among prescribing clinicians that the quality of
a wheelchair's cushioning can make or mar the patient's comfort,
affecting his physical well-being and range of activities
(Nichols, 1971). The requirement of cushioning is to offer
support, whether in the form of supplementary cushioning or as a part of the upholstery of the wheelchair. It comprises of two parts, a resilient core which provides the support, and outer cover(s) to ensure the highest level of safety, comfort and hygiene with prolonged body contact. At present, a number of alternative materials are available to provide support, including gels, polystyrene, air, and plastic balls. The most frequently prescribed material is however polyurethane foam which can be obtained in varying thicknesses and levels of resilience.

The advantages in the use of this material are cheapness, durability, light weight and ease of application. Used correctly, the material can satisfy many of the support requirements of the wheelchair user (Nichols, 1971), but where a very soft density or too thick a cushion is provided, the problems have been noted as follows.

4.3.4.2. Soft density upholstery cushions

The problem associated with the use of soft density polyurethane foam for seating support is that little control can be exercised over the distribution of pressure. With deep penetration of the ischial tuberosities into the material by body weight, loading is placed on the thigh area and will result in the frustration of venous return from the legs (BS 3044). Another detrimental factor is that of shear stress on the user's buttocks by tangential pressure that results from the surface tension of the material (Lowthian, 1970a). "Soft cushions, air rings and
similar emblems of comfort often cause discomfort and are sources of danger. Air-rings predispose to pressure sores, and deep soft cushions successfully immobilize the severely disabled". (Nichols, 1971)

4.3.4.3. Thick cushion upholstery

In providing a support cushion which is extremely thick, the difficulties of use are those of maintaining trunk stability and ease of wheelchair transfer (Mooney et al. 1971). It was found from evaluation studies on cushions by Mooney that "the use of paralyzed patients as evaluators brought out points which might have been passed over as inconsequential by normal subjects. The instability of cushion mass is a severe limitation in transfer to the cushion and stability of the patient as he sits upon the cushion trying to maintain stability against a floating reaction point".

The difficulty in specifying a totally acceptable upholstery cushion support material for wheelchair users is that the requirements and physical characteristics of the different types of users vary considerably. It would appear from studies carried out on seating both with the able and disabled population that whatever provisions are made, the probability of accommodation of all groups within one specification is remote. What can be done however is the establishment of common denominators of seating in terms of pressure, activities etc., and the translation of these in terms of recommendations.

It would seem that the first requirement of any upholstery
material is that it is mounted on a firm base that allows for a reasonable fit between the support material and the user: a firm yet resilient material that will allow for controlled pressure distribution around the ischial tuberosities is also highly desirable, providing its thickness is such that it does not frustrate wheelchair transfer or pose problems of trunk stability.

4.3.4.4 Upholstery covering material

Unless great care is exercised in the selection of upholstery covering material, the possibility exists of a complete negation of desirable features maintained in other aspects of the wheelchair's support. The necessity for careful consideration to be given to covering material exists for two main reasons, hygiene and pressure distribution.

4.3.4.5 Hygiene

The need for a wheelchair user to maintain a high level of personal hygiene is crucial to his wellbeing and comfort, as the consequences of infection can be severe, especially in association with catheter use, or where the wheelchair user is prone to skin breakdown (Nichols, 1971). All body contact surfaces of a wheelchair need to be given consideration in respect of hygiene maintenance, but particular care is essential in the choice of seat covering.

Unless a sheepskin is available, most wheelchair users when supplied with a wheelchair of the lateral folding type have
the choice of sitting directly on the PVC coated material of the wheelchair, a thin cover, or alternatively a supplementary cushion covered with a flexible material. In the specification of a plastic coated fabric for wheelchair upholstery, the advantage the material offers in terms of ease of cleaning must be balanced against those of impermeability and associated 'stickiness' (Platts, 1971). With some synthetic rubber foams used extensively for cushioning, the upholstery material must serve as an effective barrier between the user and the cushion material, as the foam itself can actively encourage bacterial growth. "In the case of both polyether and polyester foams (particularly the latter) bacteria will feed on them unless a suitable bactericide is present". (Patterson, 1963)

The common element that effects both the level of hygiene and susceptibility to skin breakdown is moisture, whether due to sweating or to incontinence. It is extremely necessary therefore to provide an upholstery that will quickly absorb this moisture without itself appearing wet. In the specification of such a material, limitations are invariably placed on the range of choice by the dangers of point pressure resulting from creases and folds. "Most cushioning materials have a surface (or surface sheet) which has a high coefficient of friction - especially if damp - and also stretch slightly under heavy loading. This places a peripheral tension on the skin under a bony prominence...The high friction encountered in damp conditions is probably caused by the hygroscopic nature of linen and sodden (or macerated) skin, which prevents the
formation of a lubricant film (as would be the case between non-absorbent surfaces) and encourages adhesion. The effects of this adhesion (friction) is to pull the skin backwards as the patient slides forward. This greatly increases tension on the skin and its blood vessels" (Lowthian, 1970b).

It would appear from the discussion that in order to accommodate moisture and to avoid the consequences of point pressure from material creasing or folds, consideration should be given to the possibility of two layers of upholstery covering. The benefits of this would be in the provision of an inner cover which would serve as an impermeable moisture barrier with 'wipe clean' properties, and an outer body contact cover that would satisfy more adequately the absorption and smooth surface requirements. One material currently available that possesses the necessary properties for use as an outer cover, and has been shown to be ideally suitable for wheelchair upholstery is sheepskin.

4.3.4.6. Sheepskin

The first use of sheepskin as a supporting surface for the sick and disabled is attributed to Hippocrates who described its application to the prevention and treatment of pressure ulcers. (Pressley, 1963) Its use in modern rehabilitation techniques has not until recently been extensive. The reason for this was the difficulty experienced in maintaining a high level of hygiene with sheepskins because of the breakdown of the skins with repeated washing. (Pressley, 1963) With the development of new techniques of tanning, a procedure became available that allowed
for higher washing temperatures to be used in the cleansing of soiled sheepskins. The process, known as Gluteraldehyde-chrome tanning, raises the shrinkage temperature of the treated skins to a level where high temperature laundering is possible without shrinkage or matting. (Happich et al., 1969a)

Basically, sheepskins offer three main advantages in their use as a body contact material: water absorption, air circulation and pressure distribution.

a) Water absorption

The water absorbent properties of medical sheepskins are well recorded, both subjectively (Garrow and Wooller, 1970) and objectively (Happich et al., 1969b). In subjective tests, it has been found that a water content equalling 30% of the skin's weight can be supported before 'wetness' is felt. In objective tests to ascertain the moisture absorption and desorption capacity and rates, it was found that these varied with the ambient temperature at constant humidity, the optimum values occurring at about 98.6°F.

b) Air circulation

The ability of a sheepskin to accommodate or desorb relatively large amounts of moisture without apparent subjective discomfort lies partly in its treatment. It has been found in tests (Ewing et al., 1961) that Merino or Merino cross skins of fibre diameter 22\text{\mu} - 28\text{\mu} and trimmed to a uniform one inch fibre length give the conditions that allow for free circulation of air between
the fibres.

c) Pressure distribution

The pressure distribution properties of medical sheepskins have been observed from numerous test programmes carried out internationally during the last decade, notably in Australia and the U.S.A. When applied to patients in the category most susceptible to pressure degradation, the bed-ridden geriatric, it was found in studies reported by Ewing et al. (1964) that the prescription and use of treated sheepskins for these patients resulted in marked improvement, and in some cases complete recovery, from pressure sores.

4.3.4.7. Surface tension of upholstery

While it is of great importance that no creasing or folding of the surface material takes place, it is of equal importance that the surface tension of the material is such that it does not limit the provisions of the supporting surface or its cushioning. It has been found with Gel cushions (Mooney, 1971) and foam covered with stretch material (Lowthian, 1970b) that the enclosing material can have a substantial effect on the performance and quality of the support. In both cases, this shows itself in degrees of tangential stress on the body contact area.

4.4. The backrest

For a large proportion of both the able and disabled population, the requirements for seated back support will be very similar,
and based mainly on factors such as stature, skeletal display and activity. Differences of accommodation where they exist between the two populations will be associated, particularly in the case of the wheelchair, with considerations such as transportation of the system, or provisions for clinically evaluated optimum body postures.

Irrespective of the classification of its user, the function of a backrest is to provide support, particularly in the plane normal to the back. In the provision of this support, the backrest must be designed not only to satisfy the anatomical and physiological requirements of its user, but also to facilitate the body movements associated with its environmental role. Existing ergonomics recommendations for the design of back support tend, because of the multi-faceted role of the chair, to be specific to its associated role, e.g. office chair, easy chair, cinema seat etc., whereas the satisfaction of the requirements of a wheelchair user will demand an amalgam and possible extension of these. However, before an analysis of back support recommendations is made, it is thought useful to discuss the body area to be supported in the light of its structure and surface configuration.

4.4.1. The back

The main constituent part of the human back is the spinal column which is made up of five connected sections: cervical, thoracic, and lumbar regions, and the sacrum and coccyx. When vertical as in sitting or standing, the spinal system is held
in place by a balanced muscle configuration which allows a stable posture to be maintained. If viewed from the side, the spinal column of a fit and able individual is seen to conform to a double node pattern which is developed from a single node system in infancy. This development takes place as a result of upright posture achievement, and allows for the greater flexibility of spinal movement in the vertical direction. If this flexibility of spinal movement were not present, vertical impact loading from activities such as jumping or running would be transmitted directly to both the head and to the spinal discs which enable compound positioning of the trunk to be achieved. (Latchaw and Egstrom, 1969)

Although it has been calculated that only a small percentage of the body weight is transferred to the back as pressure in seating (Swearingen et al. 1962), the shape, angle and size of a backrest is critical not only to the comfort of the user, but also in the prevention of low back pain (Keegan, 1953) and muscle fatigue (BS 3044, 1958). Depending on the level of support needed by the wheelchair user, two main types of backrest will need consideration: lumbar, and lumbar and thoracic.

4.4.2. Lumbar support

An important factor on whether support in the lumbar region is adequate for the wheelchair occupant will be trunk stability. (Lee et al., 1967) For many types of wheelchair user, particularly those with good hand and arm function, the advantages of a backrest whose height falls below the level of the scapulae are considerable. With manually propelled wheelchairs, the application
of a lumbar backrest facilitates the wheelchair's operation by leaving the scapulae free for excursion (Spiegler and Goldberg, 1968), and will influence the area of arm mobility. (Brattgard, 1969)

4.4.3. Lumbar and thoracic support
For disabled wheelchair users with poor trunk stability, or where respiratory considerations require a reclining back position, a high level of support is necessary, possible in association with a headrest. (Kamenetz, 1969)

4.4.4. Backrest shape
In order to dissipate the pressure applied to the back during sitting, it should be spread over as large an area as possible (BS 3044). To do this adequately, contouring of the backrest must be considered, and has been strongly recommended in many seating publications. (BS 3044, 1958, Keegan 1953) The extent of the contour fit will depend on a number of factors including range of stature, resilience of upholstery, and whether the backrest angle is adjustable. Ideally, a backrest should be upholstered to fit the requirements of individual users (Brattgard, 1969), but in the design of a wheelchair this may not be feasible for reasons of economics and differences in wheelchair role.

Accepting this limitation, possibilities exist for the accommodation of both pressure distribution and variation in stature by providing a laterally concaved backrest that locates on the 5° lumbar curve of the back (BS 3044, 1958). By supporting the
back tangentially in the vertical plane, vertical stature variations can be accommodated for, providing clearance is given to the sacral region. (BS 3044, 1958)

In the case of lumbar plus thoracic support, subjective tests (Wotzka et al, 1969) and objective tests (Keegan, 1953) have shown that close correlation of the backrest shape with that of its user gives increased comfort and anatomical protection. To achieve this high level of correlation, it may be necessary or desirable to include a system of thoracic plane adjustment within the back support so that variations in the shape and position of the thoracic spinal node can be accommodated for.

4.4.5 Backrest angle adjustment

Where back angle adjustment of a wheelchair is considered beneficial or necessary, both the arc of movement and axis of pivot must be carefully specified. With respect to the arc of movement, two main considerations must be taken into account, the tangential loading of the buttocks, and the consequences of the shift in the user’s centre of gravity.

4.4.5.1 Tangential loading

It has been found from a number of studies usually associated with support in hospital beds that the tendency of patients seated in positions other than upright is to slip. The consequence of this slip is that shear force is applied to the skin of the buttocks, and ulceration occurs. (Reichel, 1958)

Although a difference in body configuration exists between the extended legs of the bedfast and the angled legs of the wheelchair
user, often little or no leg strength reaction is present, especially in the case of paraplegia, to counteract this slide, and the situations would therefore be comparable.

To offset this slip, an increase in seat rake angle is necessary (Nichols, 1971), with the result that the trunk/thigh angle is reduced, but the emphasis of total body position is to the rear of the chair.

4.4.5.2. Centre of gravity

To facilitate rearward tipping by attendants, most wheelchairs have the fulcrum of tip, i.e. the rear wheels, located as near the centre of gravity of the wheelchair and user as possible. To compensate for an adjustable backrest, specifications are made for an increase of between 4" and 6" in this distance (see Fig. 2) (Jebsen, 1968). Where difficulties do occur with wheelchair stability, they are usually associated with factors that negate this increase in centre of gravity/fulcrum distance, and include such things as amputation of legs, or wastage, or the conversion of manually propelled wheelchairs to power. This conversion of wheelchairs invariably involves those of the laterally slung canvas type, the frame configuration of which determines the location of the power batteries. Placed to the rear of the wheelchair fulcrum, the combined influence of battery weight and reclining backrest can render the wheelchair unstable in certain conditions. These include patient spasm, ramps, and uneven surfaces taken at speed.
4.4.5.3. Axis of pivot

The importance in the location of the pivot point of an adjustable backrest lies in the need to maintain a close correlation between the user's back and the contoured support. Unless a flat back surface is present, any variation between the pivot point of the user's trunk and that of the chair's backrest will show as a contour mismatch due to a height differential produced by the backrest adjustment. Studies carried out (Keegan, 1953) show that the best maintenance of back and backrest fit during the adjustment of arc of support is when the pivot point is in line axially with the user's hip joint.

4.4.5.4. Desirability of an adjustable backrest

In the specification of an adjustable backrest, it must be appreciated that the advantages of flexibility of posture (Brattgard, 1969) can be diminished by factors such as those discussed as well as the increased weight of the chair, approximately 33%, (Spielger and Goldberg, 1966) and also problems of adjustment, feeding, working and propulsion. (Nichols, 1971)

Because of the method of construction of many current wheelchairs, i.e. laterally slung canvas, the backrest width often equates that of the wheelchair seat. Depending on the body size of the user, this can frustrate wheelchair operation by restricting arm mobility (Platts, 1971), and it is recommended that the backrest width does not exceed that of the user's chest. (Brattgard, 1969)
4.4.6. Backrest size.

Ideally the size of a wheelchair's backrest should be related to the specific anatomical characteristic of its user (Brattgard, 1969). However, in the design of a wheelchair for wide prescription this would be difficult to accomplish for reasons of cost. It is therefore necessary to consider the specification of standard sizes to cover as wide a range of body size as possible.

Given that the backrest height of a manually propelled wheelchair should not encroach into the scapula area, the recommendation of around 16" (Spiegler and Goldberg, 1968, Hoberman et al., 1953) for adults is generally acceptable. Where higher levels of back support are required, these will be determined by conditions such as neck muscle strength and the need for head support.

4.4.7. Backrest upholstery

Because of the reduced pressure factor, the specification of backrest upholstery is not quite as critical as for the seat, but still remains important in the maintenance of the user's comfort and the preservation of good posture. Providing an adequate contoured fit is achieved between the user's back and the supporting backrest, 1" of foam rubber should be adequate unless the user has particularly bony or prominent scapulae. (Lee et al., 1967, Keegan, 1962)

Covering or body contact materials used with the wheelchair's backrest should be given the same considerations as those used in the seat (Lee et al., 1967), and should maintain the same properties of pressure distribution, moisture absorption and
crease free display.

4.4.8. Notes on the backrest

It should be accepted that no one backrest design can possibly satisfy all the requirements of the disabled wheelchair user. Specifications and recommendations made and discussed have been related to the backrest as a supporting surface, and it is appreciated that particular factors such as wheelchair transfer through the back of the wheelchair will by necessity determine different criteria of design. However, the areas discussed in relation to the backrest represent factors that need consideration irrespective of the particular and secondary functions of the support.

4.5. Headrests

There are two main reasons for the provision of a headrest with a wheelchair, firstly, the need to support the user's head in the case of weakened neck muscles, and secondly where semi-reclining or fully-reclining wheelchairs are prescribed. Unless special provisions have been made for an individual, two basic systems of head support are available: the back extender used mainly with laterally folding wheelchairs, and the high-backed 'winged' type.

4.5.1. Back extended head support

This system of head support is based on the extension of the wheelchair's backrest by the addition of laterally slung material. Depending on the size or particular requirements of the user, the height of the extension can be varied either by a selection
from a range of sizes, or by the application of a sliding mechanism.

4.5.2. 'Winged' head support

The advantage of the 'winged' head support over the extended back system is that lateral as well as normal support is provided. For this reason it is of particular benefit to cerebral palsy sufferers, especially among children. "For the proper functioning of the so-called righting reactions, and particularly for balance and vision for many patients with cerebral palsy and other wheelchair users, the upright position of the head is most important". (Kamenetz, 1969)

The configuration of the 'winged' head support is that the backrest of the wheelchair is increased in height and padded 'wings' applied to project forward either side of the user's head. Accepting the need for head support with certain types of wheelchair users, as "for reclining or if the neck muscles are insufficient the head must always be supported" (Kamenetz, 1969), difficulties are experienced with their use.

"Headrests often cause difficulties. Most wheelchairs can be fitted with a headrest extension, but this follows the line of the back of the chair and thus is often not in the best position to support the head. Simple neckrests and headrests can be made to attach to the wheelchair headrest extension, and they are best when custom-built. Attempts to support a very weak neck are most likely to succeed when the back of the chair is reclined at an
angle of 30 to 40 degrees. It is particularly difficult to provide adequate support for the head of a patient with severe head tremor. A well padded winged headrest gives some support and exerts partial control of the tremor as well". (Nichols, 1971)

4.5.3. Head posture

The position of the head relative to the trunk is determined largely by two factors: accommodation to activity, and weight shift in compensation to the position of the body segments below. (Lowman and Young, 1960) It has been established in tests carried out with fit adult males and aircraft seating that over an eight hour period neck discomfort was experienced irrespective of the presence of head support. In this evaluation programme, it was found that the best levels of neck comfort were achieved with an unsupported head. The reason given for this failure with the head supports provided was that adjustability of the systems to accommodate for variation of head posture was not included. (Slechta et al., 1957)

4.5.4. Specification of a headrest

Irrespective of the advantages or disadvantages of a headrest for general prescription, sections of the wheelchair population will need a head support system. Basically their requirements will fall into one of two main categories: support of the head and control of the head.

4.5.4.1. Support of the head

With the prescription of a semi- or fully-reclining wheelchair,
the benefits of such chairs are gained, in terms of weight transfer, when back angles of $30^\circ$ plus are achieved. (Swearingen, 1962) In such cases, the support of the head must be made by the wheelchair, as control of a head mass equalling approximately 7% of total body weight (Braune and Fischer, 1889, quoted by Duggar, 1962) will be extremely difficult for those with reduced muscle power. (Nichols, 1971)

Depending on the time scaling and activity of wheelchair occupancy with a reclining backrest, different levels of head support may be necessary. With the fully reclined chair used for rest periods or reduction of buttock pressure, accommodation of head posture can be made with the back extension system and a pillow, as the overall configuration of the wheelchair differs little from that of a bed. (Kamenetz, 1969)

Where a semi-reclining back is used, wheelchair activity will require a system of greater flexibility accommodating for variation in height of support and angle of presentation (Nichols, 1971). The design of the system will also need to include features such as lateral contour to help in the dissipation of contact pressure, and resilient upholstery. Depending on the range of activities of the user, the size, contour and type of upholstery of the support will require consideration as any containment of the head may limit the user's physical potential, and maximum use of the wheelchair. (Nichols, 1971)

4.5.4.2. Control of the head

For a certain minority of wheelchair users, the provision of
a supportive headrest will be insufficient in that a greater control over involuntary head movement is required. This control may be exercised by the provision of a lateral or 'winged' headrest, or the application of more elaborate systems involving head suspension by vertical linkage to the chair. (Kamenetz, 1969) Where these or other systems are required, it will be necessary to consider this development and design as the concern of the prescribing clinician and his technical staff.

4.6. Armrests
The design of a wheelchair's armrests will reflect considerably the level and type of user disability and also much of the role the wheelchair is to perform. Common features that are shared with the armrests of 'normal' seating are those of lateral body support and the enhancement of posture.

In its association with the wheelchair, the provisions of the armrest will require an extension of those features not only in terms of body support, but also in consideration of the wheelchair's multifaceted role. Factors relating to the design of wheelchair armrests can be discussed in one of three areas of concern, stability, transfer and activity.

4.6.1. Stability
Many types of disability and disease exist that will result in the necessity of a wheelchair, and their common denominator is loss or reduction of function of the legs. The consequences of this loss extend not only to the use of legs in walking, but often to their role in seated body stabilisation. Where this
loss exists, it is in many cases compounded by the lack of trunk musculature at varying levels. (Grall, 1971)

To control and stabilise the user's position in a wheelchair, a number of systems including the reclining back, body harness and lateral supports have been used. For the vast majority of wheelchair users, however, trunk stability can be provided at a high level by the application of adequately designed armrests.

The primary function of armrests is to stabilise the user's trunk by reacting to arm location. In the achievement of this stabilisation, a maximum seated pressure reduction of 12.4% of total body weight can be made. (Swearingen, 1962) This reduction in seated pressure, while being advantageous to the buttocks, can, unless controlled, have serious consequences for the user's arm mobility. "The significance of segmental slowing in the wheelchair-bound patient cannot be underestimated. Patients confined to wheelchairs are depending upon their arms and hands for functional and vocational achievements. Ulnar intrinsic weakness which needlessly develops secondary to wheelchair elbow pressure should be avoided. It is suggested that nerve conduction studies be performed on these patients and when slowing is found suitable padding be supplied to reduce this pressure, and the patient be cautioned against applying pressure to the ulnar groove area". (Crane and Raptou, 1969)

Apart from the padding of armrests to protect against ulnar nerve damage, factors such as armrest height, width, distance
apart must be considered. "The armrest must be of the right height for the individual. With too high armrests the shoulders are uncomfortably raised. Too low armrests cause the back to slump, resulting in pain in the muscles. It is therefore essential that the armrests be individually adjustable."
(Brattgard, 1969)

4.6.2. Armrest height

"The specific height (of armrests) is best determined by trial with an adjustable armrest". (Spiegler and Goldberg, 1968)

However, where factors other than anthropometric considerations e.g. cost etc. determine a fixed height armrest, a standard height must be decided upon.

Made in relation to existing anthropometric data on the disabled, any specific height will by necessity exclude certain wheelchair users, particularly those at the extreme ends of variation from an 'average' size. Because of the paucity of sample data on the disabled population, difficulties exist in ascertaining both the 'average' size and the cut-off points within the user population determined by a particular specification.

Until detailed information on the disabled population is available the only alternatives to the designer are: individual user consideration, range of adjustability, or transfer of data from other sources. One source of data which are available for transfer to the design of wheelchairs is that obtained in satisfaction of the seating requirements of the able population. "Standard
models (of wheelchairs) come equipped with arms 9" above the seat which is the average for the furniture industry". (Hoberman et al., 1953) In view of the lack of more detailed information, it seems reasonable for this dimension to be applied as a standard armrest height, especially when possibilities exist for some adjustment through cushioning. "The height of armrests may be critical for some patients, and the relative height depends on cushioning. A high cushion lifts the patient up and he may then find the armrests relatively low. This can be corrected by increasing the depth of padding of the armrests". (Nichols, 1971)

For patients with particular disabilities, association with a slightly higher armrest than that determined by humerus length has been recorded as follows: "Patients with trunk instability, e.g. high spinal cord lesions, will frequently find that higher armrests will allow better trunk control by allowing utilization of shoulder depressors with the forearms resting on the armrests". (Spiegler and Goldberg, 1968)

4.6.3. Armrest shape

Depending on the type of wheelchair and its source of manufacture, the support surface shape of most armrests will take the form of unclad metal tube or upholstered arm support pads. (Kamenetz, 1969) When related to the requirements of different types of wheelchair users, both systems have advantages, either in the dissipation of arm contact pressure or reduction of armrest width.
4.6.3.1. Metal tube armrests

The main advantage of metal tube armrests are those of reduced armrest width and rigidity of construction. With disabilities such as paraplegia where good hand and arm function are present, a reduction in the overall span of the wheelchair's armrests is beneficial to the propulsion of the wheelchair in terms of handrim access. (Kamenetz, 1969)

During wheelchair occupancy, the paraplegic is instructed to redistribute his weight over his buttocks by lifting his body from the chair in a wheelchair push-up. (Fordyce and Simons, 1968) The facility offered by metal tube armrests during this activity is in the form of stability of surface and flexibility of hand location. (see Figs. 3 and 4)

4.6.3.2. Armrest pads

"When patients are confined to their wheelchairs for long periods it is more desirable to have the flat wooden or the upholstered armrests". (Deaver, 1949)

"Attention should be given to the type of surface on which the elbows and feet rest, as about 33% of the sample said sores developed on their elbows, heels, toes and sides of their feet". (Platts, 1969)

"Unless otherwise specified, all wheelchairs are fitted with plastic armrests. However, experience has shown that upholstered armrests are far more comfortable and offer better leverage and grasp for patients who use the arms for support in getting in
Fig. 2. Reclining wheelchair with set-back rear wheels

Fig. 3. Metal tube armrests

Fig. 4. Use of armrests in relieving seating pressure
or out of the wheelchair". (Lowman and Rusk, 1960)

The function of armrest pads is to dissipate the arm contact pressure produced in lateral support of the body. To do this adequately, the pads must be of a reasonable size and level of upholstered resilience. In the determination of pad size and type of upholstery, it is necessary to consider these features in relation to others such as wheelchair activity.

In terms of activity, limitations imposed on the dimensions of armrest pads will be those of approach to objects such as desks, tables etc. (see Fig. 5) for pad length, and manipulation of handrims for pad width. Where the wheelchair user requires support in standing, the facility of upholstered arm pads at the front end of the armrest is highly desirable, and can be achieved by the provision of reversible desk arms. (Lowman and Klinger, 1969)

4.6.3. Desk arms

The configuration of desk arms is such that a foreshortened arm pad located on a stepped armrest allows a closer proximity to work surfaces. With the armrest reversed, the location of the pad at the front of the chair aids standing and enables the user to have better access to the chair's handrim. (Lowman and Klinger, 1969) (see Figs. 6 and 7).

4.6.4. Armrest width

Apart from the factor of handrim accessibility, the aspect of
Fig. 5. Full length armrests

Fig. 6. Desk arms

Fig. 7. Desk arms reversed
a hand grip dimension must also be considered in the determination of an optimum armrest width. Where the armrests are used as an aid to transfer, as in the case of double above-knee amputees or paraplegics, hand and arm strength will play a large part in the success of the developed techniques. (Nichols, 1971) When hand connection is made with the armrests in transfer, the stability of the technique will be a function of handgrip strength. Unless the width of the armrest is related to hand size, the quality of hand grip will be diminished.

Recommendations relating to hand rails, which perform much the same function of body stability, maintain a 1\(\frac{2}{5}\)" - 2" diameter section. (Goldsmith, 1963) When applied to wheelchair armrests, a derivative of this section in the form of a parallel segment in the plane of the wheelchair seat will be required to give arm pressure dissipation and ease of attachment of the armrest pad to the rail of the armrest.

4.6.5 Upholstery of armrests

Unless contoured to arm activity, the support pads of the armrests will require upholstery. "All armrests should be padded except those of a veteran wheelchair user who indicates he prefers to use them without padding". (Spiegler and Goldberg, 1968) With most current wheelchairs, this takes the form of polyurethane or similar foam covered with a plastic fabric. "Of those commenting about armrests, 24\% said they were uncomfortable, or painful, to lean on. The construction was said to be too hard. Complaints were made that the covering material was too
slippery, and that it quickly wore to a shabby appearance".

(Platts, 1971) In situations where extensive use of the armrests will be made, factors such as levels of padding resilience and durability of material covering may require the features of adjustment or replacement, and these aspects will need consideration in the design of the armrest support pad.

4.6.6. Armrest spacing

"Among the people who supply or sell wheelchairs, there is a very widespread 'you-must-be-comfy-dear' attitude which leads many disabled persons to acquire chairs which are much too large. Apart from the obvious fact that it is more difficult to get into small lifts or pass through narrow doors, the idea is a mistaken one because there is no real comfort in flopping about in a chair which is too wide and therefore cannot give proper support at the waist. A good practical rule is to regard so-called 'Junior' models as standard ones and treat the official 'Standard' models as outsize ones". (Carcasson, 1963)

As with armrest height, the spacing of armrests should ideally be the product of individual consideration, taking into account factors such as body size, disability and accommodation of orthotic aids. "The type of seat, back and armrests must be adapted to the degree of handicap". (Brattgard, 1969) Where a compromise dimension is required, as in the case of a standard wheelchair, a balance of these factors must obviously be made. However, depending on the design of the armrests and the technique of attachment, these variables can be reduced. Accepting that the primary function of the armrests is to provide support
to the body, their proximity should be such that symmetrical support can be offered within the elbow range of the user without the necessity of lateral body shift. A determining factor in the minimum width of armrest spacing for any individual will be that of hip size and therefore chair access. With most current wheelchairs, particularly the lateral folding type, armrest width is a product of seat size, although some adjustment is available with offset arms (Kamenetz, 1969). Where the design of armrest can reduce the effects of variation in hip/waist ratio and also the presence of leg orthotics is in the location of the armrest support struts and the proximity of skirt guards.

It has been suggested that the optimum dimension for armrest spacing should be at least the thigh width, (i.e. seat width, less two inches) thus giving close support to the user's body. (Feeney, 1969) Anthropometric data available for the able population and applied to furniture design recommend that for the majority of the population an armrest width of 19" will allow the sitter sufficient width to change position without losing the support he needs. (Branton, 1966)

4.6.7. Transfer

The role the armrests play in wheelchair transfer is an important one in that unless their design features are related to the requirements of transfer, limitations of activity and user independence can occur. Unless physically lifted into the chair by an attendant or hoist, the user, depending on his level of
disability, may require access to the wheelchair by any of its sides.

The level or type of disability of the user will play a large part in determining the method of transfer used, and the direction of approach: "Wheelchair users who are unable to stand may be able to learn to transfer forwards, sideways, or backwards through the back of the chair. The technique used considerably depends upon the strength of their arms, and on whether they can use their legs as props or counterweights. Paraplegics who have full use of their arms develop powerful upper-limb and upper-trunk musculature, and can take their full body weight on their hand and arms, enabling them to transfer in different ways depending on circumstances. Those less physically strong, and patients with weakness or deformity of the upper limbs will have greater difficulty in transferring, and will depend much more on having the chair, seat, bed and toilet at the same heights. For them, the position of the chair during transfers is critical, and needs careful adjustment. They may need such transfer aids as a sliding-board or monkey pole to help them. Transferring sideways depends on the patient's ability to remove the armrests from an appropriate wheelchair". (Nichols, 1971)

The removal of an armrest to facilitate transfer can be made in a number of ways, including its complete detachment or a pivoted swing. Irrespective of the type of system applied, the important features to be considered are those of unrestricted access and safety. In developing techniques of transfer to and from his
wheelchair, the disabled user often makes use of body momentum to achieve the operation, and any armrest design feature that unnecessarily frustrates these movements is undesirable.

This facet of unrestricted approach extends to the use of the transfer board which is used to span the distance between the wheelchair and other supporting surfaces such as beds etc. Because the safety of the user is dependent on the security of the board's location, the design of armrests and their method of wheelchair location should allow for unobstructed bridging. Where possible, the located armrest should be locked so as to ensure stability and safety, not only in respect of the chair's user, but also for procedures of lifting and manoeuvering by attendants. "Pin locks and button spring locks are available to fasten and lock removable arms securely to the chair. One or the other must be in the prescription to assure safety". (Lee et al., 1967)

4.6.8. Activity

The design of armrests should include consideration of the possible activities of the user, whether through their configuration or in the facility of easy replacement. Depending on the height of the wheelchair, close proximity to tables, desks etc. will not be possible with extended armrests. For cerebral palsy and other patients who benefit from the addition of a wheelchair tray, the location and connection of this feature will be made via the armrests. Where possible, flexibility of design should allow for an extension in the scope of the armrest, as in the
case of reversible armrests, so that maximum use can be made of the wheelchair.

4.7. Legrests

Legrests are that section of the wheelchair between the seat and the footrests. There are two basic systems of wheelchair legrests, the side mounted type and the centrally mounted type. Although differences in design features exist, the function of both is identical. Currently the most widely applied system is the side mounted type, usually in association with laterally folding wheelchairs. Because of the varying requirements of wheelchair users, this system of legrest is made available in three categories: fixed, detachable and elevating. (Kamenetz, 1969) However, before discussion on the provisions of each category takes place, one feature of legrest design which is considered essential is described. the adjustment of legrest length.

4.7.1. Adjustment of legrest length

The adjustment of legrest length is considered a necessary feature of legrests in order to ensure for all users the alleviation of thigh pressure, (Kamenetz, 1969) and for some the further aspect of catheter drainage. "If the footrests are too high, the knees will be too high, and hips and knees will be uncomfortable. This position may also cause drainage problems for patients using incontinence appliances". (Nichols, 1971)
4.7.2. Fixed legrests

Although adjustable in length, the provisions of the fixed legrest extend only to the role of a support beam for the wheelchair footrest. When used in association with the lateral folding wheelchair, its fabrication forms a permanent part of the chair's construction. The angle of presentation of the legrest beam to the wheelchair is a product of the chair's wheelbase and front castor size. (Deaver, 1949) While being standard equipment on most wheelchairs, the provision of a fixed legrest has a number of disadvantages in that it:

i. permanently extends the length of the chair
ii. can make wheelchair transfer difficult
iii. does not accommodate for variation in leg angles.

4.7.3. Detachable legrests

Detachable legrests usually have the additional feature of sideways swing. "A swinging detachable footrest is made for those who need to get as close as possible to bed or toilet in order to transfer out of the front of the chair. It is particularly recommended for bilateral amputees with prostheses, as the footrests can be removed for transfer activities when the patient is not wearing them. It is also indicated for paraplegics and quadriplegics who do not require elevation of the lower extremities". (Lee et al., 1967)

The usefulness of detachable legrests extends to those wheelchair disabled who propel the chair by foot movement, such as hemiplegics. "But some patients will not achieve independent
walking and will require a wheelchair; unfortunately, the co-ordination required to propel a single-hand controlled wheelchair is considerable and few elderly hemiplegics are able to achieve this skill. Some of them can, however, manage to control a wheelchair in their own environment by combined activity of one hand and foot; the arm provides forward propulsion, albeit towards the opposite side and the foot controlling the direction, by acting as a brake and a pivot". (Nichols, 1971)

The main disadvantage of detachable swinging legrests is lack of accommodation of variation in leg angle. (see Fig. 8)

4.7.4. Elevating legrests

The facility offered by elevating legrests in accommodating for variation in user leg angles is considered highly desirable.

"The most neglected point is movement at the knee joint. Most of the disabled who need wheelchairs have bad circulation in their legs. The muscle-pump does not work and venous blood is not pressed up to the heart. It will be much better if there is the possibility of changing the position of the legs. Another very important thing is that movement in the knee-joint prevents contractions in the muscles, tendons and ligaments. I cannot overemphasize the fact - based on my research and experience - that every long-term wheelchair-bound person with some flexibility in his knee-joint must be able to change the position of his legs. This may be provided in an active or a passive way, but if it is not provided, it is criminal. Movement must be effected in the axis of the knee joint. Any other location will disturb the
correct distance between the seat and the footplate". Brattgard, 1969)

The difficulty in offering solutions to the problems of correlation between point of legrest pivot and axis of knee joint is in the factor of wheelchair transfer. Because the axis of the user's knee lies above and forward of the chair's seat front edge, any system, unless detachable, will frustrate ease of sideways transfer to the wheelchair. With conventional systems of elevating legrests, the pivot point lies a little below and back of the seat front edge, thus allowing freedom of chair access. Variation in leg length relative to the seat which is produced by the change in leg angle is accommodated for by the legrest length adjustment. Currently, most systems of leg elevation are used in association with reclining wheelchairs (Lee et al., 1967), but comment on the effectiveness of their present form has been made as follows: "Elevating legrests are almost invariably the cause of difficulties. They are awkward for the patient to operate unless he can take the weight of his legs off the legrest before elevating and lowering them. They considerably increase the length of the wheelchair, making it difficult to manoeuvre in a confined space. Many patients find it uncomfortable to sit with their legs outstretched, and can only achieve comfort by sitting in a reclined position. But unless a wheelchair with a special reclining back is provided, comfort can only be obtained with considerable padding and cushioning. This will alter the patient's position in the chair and so necessitate alterations in the length of the footrest."
Thus, elevating legrests often provoke more discomfort than that for which they were prescribed. It is often easier to advise the use of a simple footstool. (Nichols, 1971)

Even with the difficulties related above, certain conditions and disabilities, such as circulatory problems (Spiegler and Goldberg, 1968), or fusion of one or both knees (Fowles, 1959) will necessitate the provision of elevating legrests to wheelchairs other than reclining. In such cases, the possibility exists that some of the limitations of use associated with side mounted elevating legrests could be reduced by the application of centrally mounted legrests.

4.7.5. Centrally mounted legrests

Although not compatible with fabric slung laterally folding wheelchairs, centrally mounted legrests can be designed to include all the desirable features of side-mounted legrests with the added advantage of wheelchair space reduction. This reduction in wheelchair size shows mainly in the area of the footrests used in association with this type of legrest.

Being mounted centrally, the footrest width is determined by the user's foot width, and not, as in the case of side-mounted legrests, by wheelchair width.

4.7.6. Legrest pads

With high leg elevation, provision of calf support pads will be necessary for the wheelchair user. "Adjustable legrests
with panels are particularly advantageous to patients who cannot flex the knees to a $90^\circ$ angle, and for other patients as an aid in return circulation". (Hoberman et al., 1952) When used in association with side-mounted legrests, these usually take the form of lightly padded panels connected to rotate axially on the legrest stem to the support position. (see Fig. 9) Where a reduction in calf contact pressure is required, a contouring of the pads to the leg shape will achieve this. (Fowles, 1959)

4.7.7. Legrest length

Because of the number of variables involved such as leg angle, leg length, catheter drainage, sitting pressure etc., the specification of a fixed distance between the wheelchair seat and footrests for a range of users is impossible. In the accommodation of the seating requirements of the able population, factors such as leg extension and angle would be satisfied by a free floor area directly in front of the chair. With wheelchair design, physical conditions such as leg spasm and athetosis often require control by the leg support mechanism, and this will necessitate a close relation between the structure and the presentation of the user's legs. As a guide, and accepting the necessity of leg length adjustability, the recommendation of a 16" - 17" seat height (Branton, 1966) made for the able population could be transferred to wheelchair design. However, this dimension could only be considered as a minimum from which the accepted range of 6" adjustment in legrest length could be made.
Footrests

In addition to their role as a supporting surface for a possible 18% of seated user body weight (Swearingen et al., 1962) the design of wheelchair footrests is often required to include other features such as foot retention. This may take the form of heel loops to ensure that the user's feet do not foul the chair's revolving castor wheels, or in the case of cerebral palsy sufferers, toe loops to control leg spasm. (Lowman et al., 1969)

Depending on the disability of the user, footrest design will be required to accommodate for activities such as wheelchair transfer, foot propulsion, or the facility of close wheelchair proximity to other structures etc. (Nichols, 1971) (see Fig. 10)

The relationship of footrest design to these activities can be made in association with legrest design, as in the case of swinging detachable footrests. "Removable swinging footrests, standard equipment on many chairs, are helpful for transfers and movement in narrow quarters; when removed they reduce carrying weight by 5lbs. The removable swinging feature adds negligible weight and little or no cost". (Spiegler and Goldberg, 1968)

Irrespective of the number of derivatives or permutations a design of footrest may have, its basic roles can be defined as: support, control, and compliance with activity, and these factors will remain constant for any alternative provided.

Support

The footrest step plate or plates will vary in area depending
Fig. 8. Swinging detachable legrests

Fig. 9. Calf pads fitted to reclining wheelchair

Fig. 10. Raised footrest
on the shoe size of the user, and whether an extension is required for toe and heel loops. "Standard step plates are approximately 6" by 6". If the patient has a large foot (male shoe size 10) or has extensor spasms, step plates which extend 2\(\frac{1}{2}\)" forward may be desired and toe loops can be attached to them. This reduces the tendency to develop forefoot contractures and ulcers under the metatarsophalangeal joints. Step plates which extend 2\(\frac{1}{2}\)" rearward are also available". (Spiegler and Goldberg, 1968)

With legrests other than elevating ones, the angle of their presentation relative to the wheelchair seat results in a leg posture forward of the 90° knee position. To accommodate for this slight elevation of the legrest, the footrest plane must also be angled to retain the relationship of approximately 90° between the user's feet and legs.

4.8.2. Control

There are two main causes of unintentioned foot displacement in wheelchair use, firstly leg spasm, and secondly loss of leg muscle power. In each case provision must be made through the design of the footrest for their control. This may be achieved as previously discussed by toe and heel loops (Spiegler and Goldberg, 1968), but alternatives to this system are available and can be applied where necessary. One such alternative would be in the integration of the user's footwear into the foot control system. "Also considered in the design of the footrests were the difficulties experienced by subjects with athetosis,"
the symptoms of which had been controlled previously with retention belts. It was thought on aesthetic and psychological grounds that some provision should be made to accommodate intrinsically some method of leg control. This was achieved by restricting the foot contact area to the sole of the subjects' shoes and using the remaining gap between this and the heel support to trap the heel of the shoe securely, thus ensuring that no involuntary movement could take place". (Cunniffe, 1970)

4.8.3. Activity

To conform to the user's activities, footrests are made in the possible combinations of detachable, swinging, split and elevating. Their use may be in association with wheelchair transfer, access mobility and/or proximity to other structures. (Nichols, 1971) For any system of foot support to attempt through its design the accommodation of all the possibilities of uses and combination of environments would be impossible. However, there are basic requirements which need satisfaction, and these can be listed as follows:

i. freedom of access to the wheelchair, unimpeded by the footrests

ii. the facility of footrest swing or removal, possibly in association with the legrests.
CHAPTER 5

5. The wheelchair as a dynamic device

5.1. Introduction

So far in the discussion of the wheelchair as a structural concept, the analysis of its role has been related mainly in the provision of static support. In this discussion, differences in the requirements of wheelchair users have been associated, where they exist, with design features that offer solutions on the level of the highest common denominator. Irrespective of the type of disability, there exist within the total range of wheelchair users many similar characteristics that can be accommodated by general specifications or an established range of adjustment.

In the consideration of the wheelchair as a static support, the effectiveness of these specifications will be the product of a number of factors including large sample data collection, research and evaluation. Where substantial differences show in the design of wheelchairs and their relation to the various types of user is in the method of wheelchair propulsion.

Basically there are three methods of wheelchair propulsion. They are: self propelled, attendant propelled, and motorized. Although a number of current wheelchairs have the facility of adaption to perform any or all of these roles, a conflict of role must exist, and is often shown in factors such as centre of gravity, braking, and/or wheelchair control. Because of the amount of information concerning wheelchair control, this
will be discussed in a separate chapter.

5.2. Centre of gravity

The position of a wheelchair's centre of gravity and its relationship with that of the user is considered an extremely important factor. Its influence extends to areas of wheelchair role, user safety, and the type of disability that can be accommodated.

Although of equal importance in the design of wheelchairs relating to the three methods of propulsion, the factor of centre of gravity has a variation in emphasis for each derivative of wheelchair design. Before discussing the variation in emphasis determined by the type of wheelchair, it is necessary to consider the influence maintained by the user's body mass centre of gravity, and the factors relating to its establishment.

5.2.1. Body mass centre of gravity

The determination of body mass centre of gravity can be established in a number of ways. Two methods that have been used with some frequency are the body tilt vector and the water immersion method. Although differences exist in the procedures of the two systems, both operate from a basis of distance related body mass, and can be described as follows.

5.2.1.1. Body tilt vector method

This system of determining the body mass centre of gravity
involves the balancing of a fixed body configuration in two planes relative to an established reference point. The point of intersection of the two vectors produced from body balance in the two planes identifies the mass centre of gravity of the body.

5.2.1.2. Water immersion method

This system of centre of gravity determination is less accurate than the above method when used in association with total body mass, the results being obtained from the assumption of constant density in any body segment. The method used is based on the equation of moments about a given point, as follows:

\[ V \cdot \text{sg} \cdot x = v \cdot \text{sg} \cdot \bar{x} \]

where

- \( V \) = total body volume
- \( \text{sg} \) = specific gravity of body material
- \( x \) = distance of C of G of total mass from reference point
- \( v \) = volume of any 1 lamina, \( n \) of which make up total body volume
- \( \bar{x} \) = distance from reference point to mid-point of lamina

Total body volume is found by the amount of water displaced by complete immersion of the body, and that of lamina volume by increment immersion. (Drillis et al, 1964)

5.2.1.3. Position of centre of gravity

Although it has been established that a number of factors can influence the position of the body's centre of gravity including age (Swearingen and Young, 1965), and somatotype (Drillis et al,
1964), studies carried out on adult males (Swearingen, 1962) show that for a given body position, the centre of gravity of at least 90% of the adult male population falls within a sphere 2" in diameter. In the seated position, the centre point of this sphere lies 9\frac{3}{8}" vertically above the seat plane and 8\frac{3}{8}" forward of a 90° back plane. This point of centre of gravity location equates approximately with both sexes. (Swearingen and Young, 1965)

Within the seated position, and with buttock contact maintained, the axis of the centre of gravity sphere location has been found to extend with the parameters of body movement to a maximum distance of 12" vertically and 15\frac{1}{8}" horizontally from the 90° seat and back reference planes. (Swearingen, 1962)

In addition to the necessity for accommodation of centre of gravity shift through intentioned movement of the user's body, other factors such as limb atrophy and limb amputation as well as body spasm will require consideration. This may be reflected in wheelbase length, footrest weighting or retention belts etc., and will be discussed further where applicable in the following sections.

5.2.2. Manually propelled wheelchairs and centre of gravity

The resultant centre of gravity of a manually propelled wheelchair and that of its user will in a number of instances require adjustment in relation to the wheelbase of the chair. This adjustment may be the result of wheelchair role, or specific
disability of the user, as in the case of a bilateral amputee.

In the majority of cases, manually propelled wheelchairs are associated with users who have good hand and arm function, often developed to a capacity in excess of that of the normal population. In the application of this capacity to wheelchair activity, the range of activity is often closely related to individually developed skills based on wheelchair balance. This may show in activities such as kerb climbing or ramp negotiation, which give an automatic extension to the independence of the wheelchair user.

In cases such as these, it is desirable to have the vertical plane of the resultant centre of gravity of the chair and its user relatively close to the axle plane of the rear wheels. The proximity of these two planes will be dependent on a number of specific factors including trunk stability and operating environment.

Depending on the type of wheel configuration adopted for the chair, this can have a substantial effect on the location of the resultant centre of gravity and the chair's stability in use. With the castor wheels located either at the front or the back of the wheelchair, the foreshortening of the chair's wheelbase by the revolving action of the castors produces a change in the relationship between the wheelbase and the centre of gravity. This change in the position of the resultant centre of gravity can result in wheelchair tip, and must be considered as a factor in wheelchair design. (Kamenetz, 1969)
5.2.2.1. Amputees

"Without a wheelchair, the activity of a bilateral amputee may be severely limited by the geography of his garden path and the streets near his home. For those patients for whom powered outdoor transport is not desirable, a wheelchair immediately increases the range of activity, and makes the possibilities of re-employment more realistic. The choice of wheelchairs is important, since the centre of gravity of a bilateral amputee seated in a wheelchair is very different from that of a normal person. Ordinary wheelchairs are liable to tip backwards when going up a slight slope, or even when at rest if the patient leans back suddenly. This makes it necessary to provide a special amputee chair, with rear wheels set some 4 - 6 inches (10 - 15 cm) further back than usual. And since the advantages and disadvantages of front- and rear-wheel propulsion are equally applicable to bilateral amputees, the most suitable chair for their use is a folding, rear wheel hand propelling chair, with the rear-wheel axle set back". (Nichols, 1971)

This rearward movement of the wheelchair's back wheels to compensate for the shift in body mass centre of gravity can present difficulties in the chair's propulsion. By extending the wheelbase back, the relationship between the position of the user's body and the presentation of the handrims used in propulsion is changed. Because of the constant arc of the handrim, the effect of a rearward movement of the back wheels on ease of propulsion increases at a rate in excess of the proportional distance. (Cole, 1969) In view of this factor, a closer proximity of the rear wheel position to the resultant
centre of gravity would be desirable, providing the stability of the wheelchair could be maintained.

Increases in the wheelbase of wheelchairs for amputees have been specified as $1\frac{1}{4}''$ (Spiegler and Goldberg, 1968) and $2\frac{1}{2}''$ (Fowles, 1959) Because of the technique of front transfer often preferred by amputees (Nichols, 1971), the recommendation of 15 - 20 lbs sandbag weighting of the wheelchair's footrests (Kamenetz, 1969) to re-establish wheelchair balance could through its fixed location present wheelchair stability problems in transfer.

5.2.2.2. Limb atrophy

With certain disabilities associated with wheelchair occupancy, there is the factor of lower limb atrophy to be considered and related to wheelchair stability. Depending on the amount of limb wastage and the increase in trunk and arm bulk (Lewin and Brattgard, 1969) often associated with wheelchair use, the effect on the stability of the chair will vary. To accommodate for the possibility of a centre of gravity shift due to limb atrophy it may be necessary to increase the distance between the resultant centre of gravity and the wheelchair's rear axle to prevent tipping.

5.2.3. The attendant wheelchair and centre of gravity

An important factor in the determination of the optimum position of the resultant centre of gravity of the user and the wheel-
chair will be the type of wheel configuration applied to the chair. With a fixed wheel configuration similar to that currently applied to the DHSS Model 13, the absence of castor wheels necessitates controlled wheelchair tip by the attendant to achieve manoeuvrability of the chair. (Cunniffe, 1970) The ease with which this operation is performed is dependent on the relationship of the horizontal distances between the resultant centre of gravity, the wheelchair's point of pivot, and the wheelchair's pushing handles. Given that ease of wheelchair tip by an attendant is a desirable feature of wheelchair design, there are three ways in which this can be influenced. Firstly by a centre of gravity shift, secondly by the position of the chair's pushing handles, and thirdly by the addition of attendant foot bars.

5.2.3.1. Centre of gravity shift

As previously discussed, the relationship between the resultant centre of gravity, and the position of the wheelchair's back axle and wheelbase is an important one, determining the chair's stability in operation and user transfer. Viewed as both a static and dynamic device, there exists a point beyond which the wheelchair's resultant centre of gravity cannot be located if this stability is to be maintained. However, providing these conditions of stability are satisfied, it is desirable to have the resultant centre of gravity located as near the point of pivot as possible.
5.2.3.2. Position of wheelchair pushing handles

With a constant relationship between the resultant centre of gravity and the wheelchair's point of pivot, any increase in the horizontal distance between the point of pivot and the wheelchair's handles will give an increased mechanical advantage to the attendant. This increase in mechanical advantage allows the wheelchair and its user to be tipped with an increased efficiency proportional to the distance increase. The controlling facet in the determination of the extent of the handle/pivot distance will be the effect on total wheelchair length and the space requirements of the wheelchair.

"The fixed perambulator type handle of the (Model 13) chair was found to be very comfortable and well placed for height at 38" above the ground. It allowed for a male attendant of average height (i.e. 5' 8") to adopt a normal upright posture when pushing the chair. Its reach, relative to the centre of the rear axle of the chair, enabled the attendant to tip the chair easily. The one disadvantage of the handle position was found to be directly related to this distance, which caused lack of manoeuvrability due to the extended length of the chair, 5' 1". (Cunniffe, 1970)

5.2.3.3. Attendant foot bars

This feature of a wheelchair's design is included to alleviate from the attendant's arms some of the effort required to tilt the wheelchair backwards. With most currently available wheelchairs, footbars take the form of tubular metal extensions to the wheelchair frame. Usually located near and a little below
the axles of the wheelchair, the footbars respond to foot pressure in overcoming the resistance offered by the resultant centre of gravity.

Like wheelchair handles, their efficiency of operation is dependent on the relative distance from the point of wheelchair pivot, and therefore the contribution to be made to wheelchair tip will be a product of their length. The control exercised on the length of a wheelchair's footbars will be that associated with their proximity to the floor, and their encroachment into the area used by the attendant in wheelchair maneuvering.

The height of the footbars from the floor will be determined by the angle of backwards tip required, and the maintenance of distance from the wheelchair's point of pivot. Footbar proportions and location relative to the floor and other wheelchair features will be a balance of factors including angle of wheelchair tip, force required, and the effect on attendant mobility area.

5.2.3.4. Foot pressure area

With laterally folding wheelchairs, two footbars are provided. They are located near and parallel to the plane of rotation of the rear wheels. Because of their tubular configuration and parallel relationship to the floor, force applied by the attendant's foot to tilt the wheelchair backwards must be transmitted at an angle to the footbar's end. This transmission of tangential force by the attendant's foot onto the tubular section of the
footbar is undesirable because of the extremely high contact pressure on the foot, and consideration should be given to a system more compatible with the requirements of the attendant. This could take the form of footplates. (Platts, 1971)

5.2.4. Motorized wheelchairs and centre of gravity

Currently, there are two basic types of motorized wheelchairs: firstly the purpose-built wheelchair whose propulsion system has been conceived as part of the total wheelchair concept, and secondly there is the wheelchair whose motorization is supplementary to the original role of the wheelchair.

5.2.4.1. Purpose-built motorized wheelchairs

With this category of wheelchair, the propulsion system should have little effect on the overall stability of the wheelchair, providing the weight distribution of the power system is balanced equally within the wheelbase of the chair.

5.2.4.2. Supplementary power systems

Supplementary power systems are available in two forms, both associated with laterally folding wheelchairs. Differences in the two systems where they affect the wheelchair's resultant centre of gravity are in the distribution of the weight of mechanisms in relation to the chair's wheelbase. The two systems are a three-wheeled system and a four-wheeled system.

5.2.4.3. Three-wheeled system

The application of this system of motorization to a wheelchair
involves a permanent backwards tilt of the chair through an angle of $5 - 7^\circ$. (Nichols, 1971) This tilt enables the function of the front wheels to be replaced by that of a power driven single wheel located centrally in the front of the wheelchair. The problems associated with the transfer of a four-wheeled system to a three-wheeled one are described as follows: "In order to provide a stable 3-point layout, it had been found that 80% of the weight of the chair plus subject must be applied to the first third of the wheelbase measured from the two-wheeled axis". (Cunniffe, 1970)

This means that to maintain a stable system, the emphasis of wheelchair loading must lie in close proximity to the rear wheels. Considered as a static structure, the stability of the wheelchair system could be maintained, particularly as the batteries to power the chair are located behind the rear wheels of the chair. However, once the wheelchair system becomes dynamic, the situation changes, with the wheelchair tilt and battery location acting against the resultant centre of gravity, particularly in situations involving gradients.

5.2.4.4. Four-wheeled system

Although differences exist in the two systems of supplementary motorization, the common factor with each that relates to the wheelchair centre of gravity and its dynamic stability is battery location and the effect of its weight. Because of the frame configuration of laterally folding wheelchairs, the only suitable position for battery location is to the rear of the
wheelchair, supported on a removable tray bridging the chair's foot tip bars.

Depending on the power endurance required, the weight of a wheelchair's battery can vary. This variation in battery weight will reflect accordingly on the wheelchair's dynamic stability, with the heaviest batteries used producing the greatest effect. To accommodate for this influence, both systems of supplementary motorization are usually applied in association with a re-location of the chair's rear wheels to bring the emphasis of battery loading within the wheelbase.

When consideration is given to the effect of centre of gravity on wheelchair stability, an appreciation should be made of the differences that exist between the wheelchair as a static concept and the wheelchair as a dynamic one. Viewed as a static concept, the influence of centre of gravity on wheelchair stability will be governed mostly by user activity within the wheelchair, and therefore a greater emphasis will be placed on the effect of change in the location of the user's centre of gravity. However, when viewed as a dynamic system, the stability of the wheelchair will be associated more with the resultant centre of gravity of the user and the wheelchair. An example of this is the necessity for anti-tip devices for wheelchairs with too short wheelbases, (Spiegler and Goldberg, 1968) or for the three-wheeled wheelchair system. (Isherwood, 1969)

To enhance the stability of the user and that of the wheel-
chair, seat belts or harnesses are often used in association with wheelchairs. "The auto-type safety belt is suggested for patients with poor sitting balance, because a sudden stop or slight tipping on an incline or curb may cause the patient to slide out of the chair". (Lee et al., 1967)

The secure location of the user within the wheelchair by means of a seat belt ensures two things: firstly, the range of the movement of the user's centre of gravity is controlled, and secondly, it enables a relationship to be established between dynamic wheelchair stability and the forces of wheelchair braking.

5.3. Wheelchair braking systems

Although not fitted automatically as standard equipment on all wheelchairs, the application of a braking system to a wheelchair should be considered as mandatory. (Lee et al., 1976) The role of a wheelchair braking system is two-fold: it operates as a decelerative device for the wheelchair as a dynamic system, and as a motion inhibitor for the wheelchair as a static system. In the specification of a wheelchair braking system, consideration should be given to the differences that exist between the two states, so that the satisfaction of the requirements of one do not conflict with those of the other.

5.3.1. Braking of the static wheelchair

Irrespective of the type of wheelchair to which the braking system is applied, i.e. manual, attendant or motorized, the requirement of the system is wheelchair immobility. This is
particularly applicable in the case of wheelchair transfer, where the user is dependent on the stability of the wheelchair for his safety. (Fowles, 1959) To ensure this safety, emphasis should be placed on a system that enables the user or his attendant to lock the chair's wheels positively. This may be achieved in a number of ways, including foot-operated systems, hand-operated systems, or an amalgam of both.

5.3.1.1. Foot-operated braking systems

This method of wheelchair braking is associated with attendant wheelchairs, and often forms part of a dual system of brake application. Located at the rear of the wheelchair in close association with the attendant, the operating pedal responds to foot pressure which is transmitted through a mechanical linkage to friction pads positions above the surface of the wheelchair's tyres. Although mechanically efficient as a braking method (Cunniffe, 1970), certain disadvantages are thought to be associated with the foot-operated system, particularly when the rear located pedal is offered as the single means of brake application.

In a recent survey which included wheelchair type distribution, Harris (1971) showed that a large percentage of attendant wheelchair users and their attendants are elderly. By placing the responsibility of brake application solely with the attendant, the wheelchair occupant has no visual confirmation of the brake's application, nor the possibility of independent action. "A chair must be absolutely safe. If the patient ever has to
fear that his chair will let him down, he is likely to refuse to use it". (Rayner, 1962)

In view of the possible dangers associated with a single foot controlled braking system, consideration is thought necessary of a minimum specification of a joint user hand- and attendant foot-operated braking mechanism.

5.3.1.2. Hand-operated braking systems

A determining factor in the design of a wheelchair's braking system will be the chair's wheel configuration and wheel size. Depending on the type of wheelchair considered, i.e. manual, attendant or motorized, these may vary, and will require accommodation in relation to the more constant demands of the chair's user or attendant. For the static wheelchair, there are two commonly used methods of wheel lock: the wheel friction method, and the wheel bar lock. (Lowman and Klinger, 1969).

5.3.1.3. Friction method

This method involves the transmission of a force applied by the brake control mechanism to a pressure pad acting on the floor contact surface of the wheelchair's tyres. The efficiency of the friction braking system will be dependent on a number of factors including: force transmitted, resilience of the wheelchair tyres, and coefficients of friction of the contact materials.

5.3.1.4. Bar lock

With this method of braking, wheelchair immobility is maintained
by the introduction of a metal bar between the spokes of the wheelchair wheels. Attached as a permanent fixture to the wheelchair frame, the brake is operated by pivoting a hook-shaped metal bar to locate across the wheel rim section. The disadvantage of this system of wheel lock is that the quality of lock is directly related to engaged bar width and spoke spacing. In user transfer, a wheelchair fitted with this system would be susceptible to movement, and it is thought that any benefit to be offered by this system should be supplementary to another. It has been suggested that the criterion of an acceptable static wheelchair braking system should be no wheel rotation when a wheelchair loaded with a 200lb test load is positioned on a 6° slope with the front of the wheelchair pointing down the slope. (Peizer et al., 1969)

5.3.1.5. Control location

The correct location of the control mechanism of a wheelchair's braking system is extremely important, in that without free and convenient access to the brake control, the effectiveness of the system is severely diminished. From a recent survey (Platts, 1971) on the characteristics and requirements of wheelchair users, the following was recorded. "Of those who complained about the brake levers 64% criticised the position of the operating mechanism. In particular that the lever could not be reached, that the levers trapped the fingers, that the levers were too short, and that they got in the way during transfer manoeuvres".

To enable the most efficient use to be made of the wheelchair's
braking system, the following points should be given consideration:

1. The control mechanism should be located in a position as near the natural fall of the user's hand as possible, and certainly within the area of hand and arm mobility.

2. The control should be sited within seated visual contact so that knowledge of its position is assured.

3. Wherever possible, bilateral control mechanisms should be specified so that advantage can be taken of braking the chair from either side.

4. Ideally, two independent braking systems should be specified to ensure added safety.

5. Depending on the position of the control mechanism, the factor of a control extension should be considered for users who lack normal arm mobility.

6. A system of brake adjustment should be included to limit the control's range of movement when wear in the braking system occurs.

7. In the location of the control mechanism, care should be taken to ensure that its position does not frustrate wheelchair transfer.

8. The action of the mechanism should be away from the user.

9. The control mechanism should be positioned so that it cannot be inadvertently engaged or disengaged.

(Sources, Nichols, 1971, Lee et al., 1967, Kamenetz, 1969)

5.3.2. Braking of the dynamic wheelchair

The requirement of a braking system for the dynamic wheelchair
is that it should retard the movement of the wheelchair at a rate that does not adversely affect the user or attendant. To achieve this, consideration should be given to a system of braking that responds to pressure or control variation. Any system of wheelchair braking that does not include the feature of controlled retardation cannot accommodate for factors such as variation in user weight and level of stability. The design of a braking system applied to a wheelchair, whether specified for a manual, attendant or motorized wheelchair, should take into consideration factors that relate to the wheelchair's movement in all directions, including backwards. Because the emphasis of wheelchair loading occurs at the rear of the wheelchair, the susceptibility of the wheelchair to backward tip is increased with the application of its braking system when travelling in a rearwards direction. This susceptibility to tip increases with the speed of the wheelchair, and represents a potentially dangerous situation unless accommodated for in the wheelchair braking.

5.3.2.1. Braking systems for dynamic manually propelled wheelchairs

For the majority of manually propelled wheelchair users, the braking requirements of both static and dynamic situations can be met by the provisions of one of two basic systems. Each of these systems works on the application of friction to the wheelchair's tyres, and their configurations can be discussed as follows.

5.3.2.2. Lever and slot system

With this method of braking, friction is applied to the wheel-
chair tyre directly by means of a pivoted lever attached to the frame of the wheelchair. The ratio of lever lengths, which are determined by its pivot point, gives a distinct mechanical advantage to the lever end which forms the user's control. By moving the lever through an arc relative to its pivot point, the user can vary the pressure applied to the wheelchair tyre, and can maintain it at a constant level by introducing the lever into one of a series of slots cut in a metal strip attached to the wheelchair.

5.3.2.3. Over centre lever

With this method of braking, pressure is transmitted to the wheelchair tyre in a way similar to that described in the lever and slot system. Where it differs from the previous system is in the method of constant pressure maintenance. Having the facility of pressure level variation, the maximum pressure achieved can be maintained for the wheelchair in a static situation by locking the brake control. This is achieved by using a combination of the features of the brake control linkage and the tyre's resilience.

The brake control linkage is made up basically of two metal strips connected by a rivet in a way which allows relative angular movement between the strips to their greatest extended length. By attaching one end of the jointed strips to the wheelchair frame with a pivoted connection, the other end can be made to operate a pressure pad above the tyre surface. Locking of the linkage is achieved by taking the pivot point of the connected strips 'over centre' to be held by the pressure
reaction of the resilient wheelchair tyre.

Adjustment in the final level of pressure applied to the wheelchair tyre is made by varying the distance between the linkage and the metal pressure pad.

5.3.2.4. Braking of dynamic motorized wheelchairs

With currently available motorized wheelchairs, the braking system is integrated with the driving mechanism of the wheelchair in that the kinetic energy of the moving wheelchair is dissipated in overcoming the inertia of the wheelchair's motor when the electric current supplying it is cut off. The rate of deceleration of the wheelchair will depend on a number of factors including user and wheelchair weight, speed of chair, coefficients of friction, efficiency of power transmission etc.

For users with poor trunk stability, the action of an abrupt deceleration could result in loss of body balance; and it is for this reason that restraint belts are often necessary with certain types of wheelchair users. Where possible, consideration should be given to the rate of chair deceleration imposed by this system of braking to ensure that adverse user conditions are not created by the facility provided.

In addition to the motor inertia system of chair braking, a second system more positive in control must be provided, so that in activities such as wheelchair transfer the immobility of the wheelchair can be assured.
5.3.2.5. Braking of dynamic attendant wheelchairs

The provision of a decelerative braking system for an attendant propelled wheelchair is essential for the maintenance of wheelchair control and user safety. Because a large proportion of wheelchair attendants and users tend to be elderly, the forces necessary to control the wheelchair in certain situations such as on an incline are not always available. This situation can also extend to younger attendants. "Twenty five years ago, when I first started to push wheelchairs, we had one with a 'retarding brake' which made slopes safe. Nowadays, any slope or ramp is a hazard or even quite impossible to negotiate, for without a helper to 'pull back', the conveyance runs away with you and patient and nurse can hurtle down violently". (Smales, 1967)

5.3.2.6. Brake control mechanism

The location and type of control mechanism for an attendant wheelchair is of extreme importance in that without relation to the requirements and characteristics of its users, its effectiveness is diminished. In the satisfaction of these conditions, the following points should be given consideration:

1. The control handle should be located adjacent to the attendant's hand in the normal pushing position.

2. If the control specified is of a type similar to a bicycle cable type, the lever should fall within the finger extension range of the attendant.

3. The direction of operation of the control should be against the 'pull' of the wheelchair in the forward direction so that the force produced by the wheelchair
enhances the force of brake application.

4. The braking system must include the facility of adjustment, particularly if it is based on a cable link, so that maximum braking efficiency can be maintained.

As previously discussed, the facility of a single braking system to an attendant wheelchair is considered inadequate, particularly when the operation and control of the system is out of range and visual contact of the user. To ensure both the safety and well-being of the user, an attendant-operated braking system should be supplemented by a separate system for the control of the static wheelchair.
CHAPTER 6

Wheelchair control

6.1. Introduction

There are three main types of wheelchair on current prescription, namely, manual, attendant and motorized wheelchairs. Although many common features exist between these types of wheelchair, their greatest basic difference is in the method of propulsion used. This factor of wheelchair design affects many aspects of the wheelchair's use and activities, both in terms of the user and of the environment in which it can operate.

Of the three main types of wheelchairs available, the manually propelled one is possibly the most complex in terms of satisfaction of the requirements of the user and the environment in which he operates. It may, through necessity or economics, be required to perform a multi-faceted role, or, in the case of motorization, an extension of the existing one. Because of the complexity of the wheelchair's role, and the range of activities performed, the derivatives and permutations of its design features are extensive. They extend to encompass factors such as methods of body force transmission, wheel configuration, wheel size, energy expenditure, and many others.

6.2. Methods of transmitting body force

There are three ways of self-propelling a wheelchair: one is by the user's feet, the second by the action of the user's hands and arms, and a third way is a combination of both.
6.2.1. Foot propulsion

This method is commonly used by individuals with fairly good trunk balance and residual motion in the lower limbs, but with the need to protect the lower extremities from weight-bearing stress. (Lowman and Klinger, 1969) Because no hand activity is involved in the chair's propulsion, the necessity for large rear wheels and handrims is removed. This means that a more compact wheelchair is possible in terms of width, which allows greater flexibility of indoor manoeuvrability. With wheelchairs propelled in this way, whether purpose-built or adapted from existing standard ones, the activity of foot propulsion often requires that the wheelchair seat is lower than for normal wheelchairs, and that a reduction in seat depth is made. This allows the user's feet full contact with the floor, and enables the legs to be moved freely by not encroaching into the popliteal area.

A typical combination of wheel size and layout for this type of wheelchair would be front castor wheels and fixed rear wheels. Depending on the surfaces to be traversed by the wheelchair, the wheel sizes can be varied. For any obstacles such as carpets or uneven surfaces, the ease of chair propulsion will be directly related to an increase in diameter of the chair's wheels, and it is thought that unless a perfectly smooth surface is assured, a minimum castor wheel size of 8" and a rear wheel size of 12" is advantageous.

6.2.2. Combination foot and hand propulsion

This method of wheelchair propulsion is characteristically used
by stroke victims. (Nichols, 1971) Because of the results commonly associated with a stroke, and the difficulties involved in one-arm operation of standard wheelchairs, adaptations are often made to existing wheelchairs to convert them to use by this section of the disabled population. Although the level of modification of the wheelchair varies with the severity of disability and the physical characteristics of the chair's user, the following are often given consideration:

1. Lower seat height than with a standard chair
2. Shorter seat depth
3. Removal of one footrest
4. Single control to operate braking system(s)
5. Removal of one handrim
6. Removal of one or both armrests, depending on trunk stability.

The above adaptations to the standard wheelchair allow for a greater flexibility of wheelchair use, and enable the remaining physical function of the user to be maximized. Apart from the points commented on, the design of wheelchair associated with this form of propulsion is similar in nature to the standard manually propelled wheelchair, and its features will be discussed later.

6.2.3. Hand propelled wheelchairs

Within the range of hand operated wheelchairs, there are three techniques available: chain drive, lever drive, and direct wheel.
6.2.3.1. Chain driven wheelchairs

The advantage of a chain driven wheelchair over other forms of hand propelled chairs is that of reduction of body force required. This is achieved by a favourable ratio of hand to wheel displacement allowed by the mechanics of the system. Basically, the system comprises of two rotational cranks located one to each side of the wheelchair. A continuous chain links each hand control to a front wheel of the chair. Chain sprockets attached to the hand control and wheel are used to transmit the power of the rotational crank to the chair's front wheels. Depending on the ratio of the sprockets, wheel size and crank arm length, a variation in the amount of effort necessary to propel the wheelchair can be achieved. However, any reduction in the motive force applied to the hand cranks to overcome the inertia of the wheelchair will have an associated reduction in the distance travelled by the chair for each rotation of the cranks.

A typical wheel configuration for a chain driven chair would be that of fixed front and rear castor wheels. For indoor wheelchairs of this type, wheel sizes of approximately 12" front and 8" rear castors are usually specified. (Kamenetz, 1969)

The disadvantages of the system are the same as for lever driven wheelchairs, namely, lack of the facility of sideways transfer, and extreme difficulty in maintaining symmetrical phasing of the propulsion mechanism. The following discussion of these disadvantages applies therefore equally to chain driven and lever
driven wheelchairs.

a) Because of the location of the cranks or levers one on each side of the chair, and the requirement of lever strength, their presence limits the user's access to the chair to one method only, from the front. Unless the user has residual leg strength, the consequences of this limitation would be severe, particularly in association with the factor of limited arm strength that may make the use of cranks or levers otherwise desirable.

b) Unless some method is available for phasing of the cranks or levers, the effect of wheelchair movement in other than a straight line will render the symmetrical phasing of the mechanisms extremely difficult. To overcome the limitations imposed on phasing by direct links to the wheels, 'free wheel' mechanisms can be introduced into the transmission systems. These allow phasing to be maintained and adjusted, but unless a reversible ratchet system is included, the wheelchair's direction is limited to one way. This factor limits the mobility of the wheelchair, in that it cannot be reversed.

6.2.3.2. Lever driven wheelchairs

The advantages of a lever driven wheelchair are very similar to those of the chain driven chair, that is: reduction of the force necessary to propel the wheelchair. Studies published in 1969 (Cole) on lever propulsion of wheelchairs showed the following. "In designing a drive mechanism, the best handle
appears to be a lever, probably with the drive motion linked to a push movement. The lever should be placed in the prescribed area of optimal strength of movement. In all movements the right hand side tends to be stronger than the left. The force that was applied is greater through a lever than through a rim drive. Through a lever, the maximum force applied was about 55lb/ft, the minimum about 101b. A motion requiring a force of less than 101b could be attempted by more than 50% of the population (lever push 1 minute 56% > 101b).

The difficulties with lever driven wheelchairs have been discussed above in relation to chain driven chairs, but there is one important additional one, that of 'dead spots' in the mechanism.

6.2.3.3. Dead spots

With direct linking of the levers to the wheelchair wheels by a crank, there occur on each cycle of lever operation two 'dead spots'. These 'dead spots' occur when the wheel axle about which one end of the crank rotates falls on the line of the crank's transmission of force. The difficulties associated with this were commented on as follows at a recent wheelchair symposium.

"Mr. N. Capener: 'May I ask one question quite apart from the previous discussion? You mentioned the push power of lever control of the movement of the vehicle. Is it beyond the bounds of engineering capacity to devise gears which will enable you to get your power on both push and pull at the same
time, or at least one after the other? This would mean that you
could pull in one direction and then push in the other, and
this would propel the machine forward as a result of both efforts!.
The Chairman: 'Is this not established in the case of the much-
maligned lever-propelled Ministry hand-propelled tricycle?'
Dr. P.A. Isherwood: 'This is all right provided the wheelchair
is expected only to go forward. It is quite easy to develop a
mechanism which will drive on both push and pull. It becomes
very difficult to reverse such a mechanism. The Ministry
machine suffers from several disadvantages. It has two dead
spots per cycle. That is, the lever can reach a point at which
no movement occurs whatever the force applied to the lever. This
is known technically as a dead point. There are two of these per
cycle. There is also uncertainty by the user as to which way
the machine will go when he pulls or pushes the lever. It might
well start off backwards, and he has no idea unless he is
prepared to look at the cranks... Technically it is very
difficult to make a reversible push and pull input mechanism'."
(Symposium on Wheelchair Design, 1969)

6.3. Driving wheels: location

Given that the basic requirement of a direct wheel propelled
wheelchair is that the wheels should lie with the direction
of through body arm swing of the user, there are three possible
locations for hand driven wheels. These are front, central
and rear locations. (Brattgard, 1969) The choice of the driving
wheel position of a wheelchair will depend on a number of factors
including the characteristics of the user, his requirements, and
also the effect of the interrelationship of the wheels' position
with other aspects of the wheelchair's design.

6.3.1. Front located driving wheels

The physical advantages of front located driving wheels are those usually associated with limited user arm mobility to the rear of the body. (In the following quotation, an outdoor chair refers to a chair with rear propelling wheels, and an indoor chair to one with front propelling wheels.) "The outdoor chair may be easier to propel but the arthritic, with limited shoulder or elbow extension may not find this to be true. An indoor chair will be more satisfactory as it would eliminate the straining to reach backwards. The emphysema patient, on the other hand, should not have an indoor model. Self-operation of an indoor type chair may cause the body to slump forward which inhibits thoracic movement. Whenever the patient's physical condition mandates erect sitting posture, the wheels should be placed at the rear. Likewise, paraplegics and quadriplegics should always have the outdoor type wheelchair to eliminate forward slump and a resultant jackknifing". (Lee et al., 1967)

The definition of the front wheel drive wheelchair as an indoor wheelchair results from the characteristics of the chair. These characteristics can be listed as follows.

1. Shorter wheelbase
2. One foot less of turning area required.
3. Smoother ride for user.

Problems associated with outdoor use of the front wheel drive
wheelchair are:

1. Difficulty in manoeuvrability due to sideways veering
2. Susceptibility to forward tip.
3. Limitations on kerb climbing, even with an attendant.

Further disadvantages associated with front wheel drive are those of difficult sideways transfer, and the aspect of user energy output, which is to be discussed later. (Nichols, 1971, Lee et al., 1967, Lowman and Klinger, 1969)

6.3.2. Centrally located driving wheels

This particular location of the driving wheels is the least common system used, mainly because of the difficulty associated with the location of the secondary wheels. Its advantage in respect of other drive wheel positions is that it allows wheelchair propulsion without the requirement of extensive forward or backward arm reach. The difficulties with secondary wheel positioning relate to wheelchair stability and wheel base. Unless systems involving more than two secondary wheels are considered, the only secondary wheel layout that would satisfy the requirements of wheelchair stability would be the fore and aft location of the wheels on the centre line of the wheelchair. This would present difficulties of footrest positioning and kerb climbing.

6.3.3. Rear located driving wheels

By far the most common location of the driving wheels of a wheelchair is at the rear of the chair. The reasons for this frequency of specification are many, and include factors such as:
1. Ease of propulsion.
2. Wheelchair stability, particularly with reclining wheelchairs.
3. Facility of wheelchair transfer.
4. Wheelchair balance for kerb climbing.
5. Upright posture in propelling wheelchair.
7. Closer approach possible to furniture etc.
8. Easier transportation.


Although certain disadvantages do exist with the location of rear driving wheels, particularly in terms of backwards reach for certain types of disabled people, their specification is thought to enable the greatest possible use and application of the wheelchair to be made. However, the final analysis and choice must be made on the basis of individual user assessment to achieve the best possible user/chair correlation. "Choice of a type of chair involves many factors, so none of these chairs, i.e. outdoor, indoor or amputee, is automatically selected by name. The medical condition and physical limitation of each patient must guide selection". (Lee et al., 1967)

6.3.4. Some physical and other factors related to front and rear drive wheel location

The results of studies carried out with able and untrained subjects to ascertain the comparative merits of front and rear wheel driven wheelchairs have shown the following:
1. For the same task, the energy consumption and heart rate of the subjects were substantially higher with the front wheel drive than for the rear wheel drive.

2. Steering accuracy of the two wheelchairs varied considerably, the greatest efficiency being associated with the rear wheel drive.

3. The effect of training did not substantially affect the overall efficiency of the front wheel drive in respect of manoeuvrability, while training did increase the efficiency of control of the rear wheel drive system.

(Hildebrandt et al., 1970)

6.3.4.1. Effect of training on wheelchair propulsion endurance

There are two desirable factors sought from programmes of physical exercise to improve wheelchair endurance performance: enhancement of operative muscle power, and increasing the performance capacity of the circulatory system. While obvious benefits are to be derived from an increase in muscle power, as in the case of wheelchair transfer (Nichols, 1971), the advantages associated with increased work capacity and wheelchair users (Odeen, 1972) are contrasted with the following discussion: "...wheelchair driving is seen to be an activity which certainly requires relatively little exertion, even on an upward slope, but which leads quickly to localized muscular fatigue due to the use of small groups of muscles and a high percentage of wasted energy. Although it may be assumed, as has been shown, that our test persons were in as good condition as possible and were used to propelling wheelchairs, the muscle
mass at their disposal is too small and tires too quickly for the circulatory system to be loaded heavily enough. Therefore the heart is not exposed to the type of conditioning stimulus which would be necessary to improve its performance capacity. On the other hand, a relatively unconditioned heart reacts to nervous stimulation from fatigued muscles sooner and more strongly with an increase in frequency. This inconvenient situation hinders an increase in stroke volume, which is so eminently important for increasing the performance capacity of the circulatory system, and applies especially to patients with additional handicaps in the working muscles. Due to the physical load, severely handicapped persons may possibly be more fatigued than exercised. Thereby, the question of how the performance capacity of these patients can be increased becomes a special problem". (Voigt and Bahn, 1969)

6.3.5. Driving wheel size

For currently available manually propelled wheelchairs, a range of driving wheel sizes can be specified, including 20", 22", 24" and 26" diameters. The choice of wheel size for use with a particular wheelchair will depend on a number of factors such as type of disability, remaining arm function, and wheelchair transfer requirements. The following extract on wheel sizes is considered applicable: "Standard wheels are 24" in diameter and are generally the most useful size. Chairs with lightweight frames are delivered with 22" wheels unless otherwise specified. Also available are 20" and 26" wheels. Although 20" wheels reduce the speed at which the wheelchair can be propelled and
increase the power necessary to start, the wheels do not rise above seat level, and this advantage may allow unassisted side transfers by a paraplegic or quadriplegic with borderline skills. Another valuable advantage of 20" wheels may benefit patients with weak biceps, such as C5 quadriplegics; the greater distance from shoulder to handrim or projections allows positioning of the hands for propulsion with the elbows extended. Elbow extension stretches the long head of the biceps for maximum force, which adds shoulder flexion force of the anterior deltoid. Thus, in spite of the slightly reduced mechanical advantage due to the smaller wheel size, more force can be applied directly to the handrims or projections. This allows self propulsion by some patients who are unable to move chairs equipped with 24" wheels". (Spiegler and Goldberg, 1968)

6.3.6. Driving wheel tyres

Two alternative types of tyre are available for specification with manually propelled wheelchair driving wheels. They are pneumatic rubber, and solid rubber tyres. The characteristics of these two types of driving wheel tyres have been discussed as follows: "The tyres are important. Pneumatic tyres are better for outdoor use, as they have some element of springing and give a better grip on wet surfaces. But they are liable to puncture, and a puncture may render a severely disabled patient helpless. Also pneumatic tyres have a higher degree of friction with the floor than solid tyres, and thus make the wheelchair more difficult for weak patients to manoeuvre, particularly on a carpet."
Therefore, solid tyres are easier to manage indoors and on a smooth (tiled or linoleum) surface and may allow a patient to be independently mobile, whereas he might be unable to propel a chair with pneumatic tyres". (Nichols, 1971)

6.3.7. Handrims for wheelchair driving wheels

The efficiency of wheelchair propulsion will depend greatly on the quality of transmission of user force to the wheelchair driving wheels. With direct drive manually propelled wheelchairs, this force is transmitted via a handrim located on each wheel. Although primarily for wheelchair propulsion, the handrims serve the additional function of protecting the wheels' alignment and spokes. (Lee et al., 1967)

To facilitate good hand location unrestricted by the driving wheel tyre, the diameter of the handrim follows closely the specified wheel size, being approximately 2" less in diameter than the wheel plus tyre outside diameter. For users with good hand function, the section diameter of the handrim is specified as 3/4" diameter 20 SWA steel tubing. (S.T.B. Spec. TSS/V/110010/3) To enable the greatest possible wheelchair mobility in respect of architectural considerations such as doorways etc., the additional wheelchair width resulting from the application of handrims should be kept to a minimum.

With certain types of disability, the handrim diameter, material and configuration will need to be changed to make propulsion possible. "Standard handrims are chrome-plated steel and are
useful for many low paraplegics. Patients with poor grasp, e.g. arthritics, quadriplegics and even most patients with entirely normal upper extremities, find that handrims coated with polyvinyl chloride, a rubber-like plastic, provide a much better grasping surface, especially if the rims are cold or wet. Most C6 quadriplegics can propel their chairs with coated rims without projections. A snap-on rubber handrim cover is also available; some patients find this preferable to the polyvinyl chloride coating. Handrims should always be ordered, even though the patient will never use them, since they protect the spokes and strengthen the wheel.

Two other rim adaptations which are of value to some patients with hand disabilities, but which are not available with 22" aluminium wheels are:

a) two-inch vertical steel projections welded on the rim. The projections are covered with rubber caps, and pushing them with the palm or wrist propels the chair. The rim of a 24" wheel should have 12 projections and a 20" wheel should have 10 projections. If projections are desired on the wheels of light-weight frames, steel wheels must be specified. The projections may be ordered in vertical or angulated projections or they may be angulated as desired after delivery. Angulated projections may increase the overall width of the chair by approximately 2", but they often allow better propulsion.

b) Horizontally mounted Bakelite knobs are also available to provide additional purchase on the handrims, but they have
limited use and would normally be specified if the patient had previous successful experience with them". (Spiegler and Goldberg, 1968)

6.3.7.1. Double handrim propulsion

For certain types of disability where remaining limb function is concentrated mainly in one arm, the requirement of double handrim propulsion of the chair may be necessary. "An outdoor chair with a handrim modification that adds approximately 2" to the width of the chair is another device. This modification, called a one-arm drive, consists of two handrims, both attached to the wheel on the patient's unaffected side. One is a normal size rim and operates the wheel to which it is attached. The second rim is smaller in diameter, and operates the wheel on the opposite side of the chair. Simultaneous manipulation of large and small handrims, with one hand, propels the chair forward or backward. A separate skillful manipulation of one rim or the other is required for directional curves and turns. Consequently, the one-arm drive chair demands good muscles in the sound arm, good co-ordination, and good learning ability". (Lee et al., 1967)

Because the physical requirements associated with one-arm drive systems are so great, their application and use usually involve younger wheelchair users than older ones. "Wheelchairs are available with the propelling handrims for both wheels on the same side of the chair. This enables a patient to control his chair with one hand. Such chairs are very difficult to
manoeuvre and although young patients with static lesions may become very adept at their control, elderly patients recovering from strokes are rarely able to learn to manage them successfully". (Nichols, 1971)

The method of wheel connection used with the double hand rim system depends on whether the chair is a lateral folding one or a fixed, non-folding one. With the folding type, the connection is made between the wheels by a collapsing metal lattice axle which allows close proximity of the driving wheels when the chair is folded. For non-folding wheelchairs, a solid axle configuration can be specified which satisfies the mechanical requirements of the double rim system without the need for collapsibility.

6.3.8. Driving wheel spokes

The number and gauge of driving wheel spokes specified for a manually propelled wheelchair will depend on two factors: the weight of the wheelchair user, and the range of the chair's activities. For normal use and with a user weight of less than 175 lb, a 28 spoke 105 gauge wheel is recommended, and for heavier users or more demanding wheelchair use, 36 spoke 120 gauge wheels. (Lowman and Klinger, 1969, Kamenetz, 1969)

6.4. Castor wheels

Apart from certain types of glider chairs, the most common sizes of castor wheels used with manually propelled wheelchairs are 5" and 8" diameter. (Lee et al., 1967) The specification of castor wheel diameter will depend on a number of factors
including wheelchair environment, user disability, and the chair's wheel configuration.

6.4.1. Wheelchair environment

"The 8" castor makes the chair easier to propel, and enables it to move over cracks in floors and sidewalks, door jambs, rugs, and other uneven surfaces commonly found indoors and outdoors. Thus, the 8" spoked castor is generally preferred. A solid 8" castor is available for heavy duty. The 5" castor is not recommended for general use as it is serviceable only on very smooth hard surfaces such as those found in hospitals and institutions". (Lee et al., 1967)

6.4.2. Disability

Where user disability can influence the specification of castor wheel size is when $90^\circ$ knee flexion is required. With front mounted 8" diameter castor wheels, the encroachment of the castor wheels, due to their castored swing, necessitates an upward angulation of the wheelchair legrests so that manoeuvrability can be achieved.

6.4.3. Wheel configurations

There are four basic castor wheel configurations used in association with manually propelled wheelchairs, defined and discussed as follows:

1. Two castor wheels, front location
2. Two castor wheels, rear location
3. Single castor wheel, rear location
4. Two castor wheels, centre line location.
6.4.4. Two castor wheel front location

The specification of front castor wheels is by far the most common location of the castor wheel positions. In association with the two large drive wheels, this configuration allows an efficient distribution of the resultant weights of the wheelchair and its user, and presents the drive wheels within the back supported arm reach of the user. (Lee et al., 1967) The disadvantages of front located castor wheels are those associated with the limitations imposed on footrest positioning and the effect of the castoring of the wheels on wheelbase length.

Because all castor wheels rely on the displacement of the axis of wheel rotation from the vertical axis of wheel swivel to provide for wheelchair manoeuvrability, the area required by each wheel in swivelling through $360^\circ$ is greater than the diameter of the wheel. With 8" diameter wheels, the area of wheel rotation is determined by the wheel radius plus a three-inch displacement due to the wheel's castor effect. Therefore the arc scribed by each wheel equals $4" + 3" = 7"$ from each point of castor wheel pivot.

In respect of the shortening of the chair's wheelbase due to wheel castoring, the following has been recorded: "With regard to the stability of the wheelchair in such a situation, there is one factor which is seldom considered. The base of support of the chair, that is its wheelbase, is influenced by the swivel position of the front castors. The fork to which the swivelling wheel is attached is not vertical but oblique, usually curved, and the axle of the wheel is two inches or more from the centre
When the curve of this fork with the castor is pivoted forward, the wheelbase of a rear wheel drive wheelchair is lengthened by about four to five inches, a most important protection against tipping forward. The easiest way to turn the castors forward is to roll the wheelchair backward a few inches, since a castor will always swivel away from the movement of the chair. When there is not enough room to advance before retreating, the castors can be turned by hand, though this is not always easy for the wheelchair occupant". (Kamenetz, 1969)

6.4.5. Two castor wheel rear location

The wheel configuration that places the castor wheels at the rear of the wheelchair is usually associated with indoor wheelchairs. (Lee et al., 1967) This is due mainly to the difficulties experienced in balancing the wheelchair on its rear castors when surmounting kerbs etc. out of doors. The advantages of a rear castor wheeled chair are those of increased mobility due to a reduced turning circle of approximately 1 ft. (Fowles, 1959)

6.4.6. Single castor wheel rear location

The main advantage with a single rear located castor wheel is that the wheel's diameter can be substantially increased without the swivel area limitations imposed by the two castor system. With the increase in wheel size a smoother ride is achieved, less prone to the restrictions of uneven surfaces such as rugs etc. The difficulties presented by the single castor wheel configuration are wheelchair balance when kerb climbing, and
the increased possibility of wheelchair instability due to a three-wheeled system.

6.4.7. Two castor wheel centre line location

This wheel configuration is used so that the location of the large propelling wheels can be associated more closely with the arm position of the user without reducing the stability of the wheelchair. The wheel layout used places the castor wheels fore and aft of the wheelchair on a line central to the chair. Raised slightly above floor level, only one of the castor wheels is operational with the propelling wheels at any one time. This enables the manoeuvrability of a three-wheeled system to be associated with four-wheel stability. The limitations of the system are those associated with wheel encroachment into the footrest area, and wheelchair balance when kerb climbing.

6.4.8. Spoked and disc castor wheels

Two basic types of castor wheels are available for specification, spoked or disc. While both types have advantages and limitations in terms of weight or reliability as discussed below, specification of type is usually made in relation to the requirement of solid or pneumatic tyres. "Castor wheels are usually 7in (18cm) in diameter: if their diameter is any less, then it is difficult to negotiate even small obstructions such as a carpet edge or small stone or a step to an interior doorway. The combination of large (24in, 61cm) rear wheels and small (5in, 12cm) castors is particularly dangerous. Spokes are sometimes used for lightness, but they are liable to mechanical failure, and 7in (18cm) or 8in (20cm) solid castors are probably the best for general
purposes. Castor wheels are subject to considerable trauma and need to turn freely for manoeuvering. Solid tyres are therefore preferable to pneumatic tyres, which are liable to puncture and also create more friction during turning". (Nichols, 1971)

6.5. Attendant propelled wheelchairs

Although many similarities exist between attendant and user operated wheelchairs, differences occur, particularly, in the case of purpose-built attendant wheelchairs, in the handle and wheel configuration of these chairs.

6.5.1. Propelling handles

Two handle configurations are commonly used with wheelchairs performing the function of attendant wheelchairs, and can be described as the split, wheelbarrow type, and the perambulator type handles.

6.5.2. Wheelbarrow type propelling handles

This configuration of propelling handle is usually associated with the laterally folding canvas wheelchair as it allows the side structures of the wheelchair, each of which supports one handle, to be brought in close proximity for easy wheelchair transportation. Apart from the advantage of collapsibility, the presentation of the propelling handles as two backwards facing tubular projections enables a hand location to be made which accommodates the transmission of wheelchair propulsion forces without undue strain through the attendant's wrists.
In achieving a comfortable transfer of forces through the wrists of the attendant, the height, angle of presentation and spacing of the propelling handles are of extreme importance.

6.5.2.1. Handle height and angle presentation

In a recent study to find a range of wheelchair handle positions based on criteria furnished by the attendant (Willans, 1971), the following recommendations were made: "From the analysis of the data the best range of handle positions is 93 to 96 cm for height and 10° to 20° for angle". The recommended range of 93 to 96 cm approximates closely to the 38" (96.5 cm) DHSS specification for maximum height of standard wheelchair handles, which reduces through angle of presentation to 36½" (93 cm).

(STB Spec. TSS/V/110010/3 DHSS)

With respect to angle of handle presentation to the attendant, this tends to vary with the source of wheelchair manufacture, and can range between +5° and -28° measured from the horizontal. (Willans, 1971)

6.5.2.2. Handle spacing

With most wheelchairs, particularly the laterally folding type, the factor that determines handle spacing is the back width of the chair. This is due to the formation of the propelling handle from the extension of the wheelchair backrest support tubes. The spacing of the handles in this way gives a distance that equates approximately to the normal forward presentation of the attendant's arms, i.e. 19½". (Branton, 1966)
6.5.2.3. Hand grip length

The hand grip length of the propelling handle should be sufficient for the gloved hand of an attendant to grasp the handle fully without fouling the handle support tube. With current wheelchairs, a hand grip length of approximately 5" is specified. (Kamenetz, 1969)

6.5.2.4. Hand grip diameter

The diameter of the hand grip will be reflected by the requirement of a secure and full hand grip, and should fall within the range of $\frac{3}{4}''$ and $1\frac{1}{2}''$ diameter recommended from studies on hand grip strength. (Morgan, Cook, Chapanis and Lund, 1963)

6.5.3. Perambulator type propelling handles

This type of propelling handle configuration is commonly used in association with purpose-built attendant wheelchairs which do not require the facility of lateral folding. Usually associated with the four fixed wheel patterned chairs, this handle configuration is provided to offer a greater choice of attendant hand positions and angles. The difficulty associated with the perambulator type handle when used in conjunction with the fixed wheel configuration is in the transmission of the forces of wheelchair tip through the attendant's wrists. Because of the relatively small wheel diameter used with this type of chair, the effectiveness of tipping bars, if provided, would be substantially diminished. In order to overcome the limitation of tip, which is necessary for any manoeuvre, an extension of the handle position relative to the rear wheels must be made. Even
with this handle extension, which is controlled by the limitations of wheelchair volume and environment, the full weight of the occupant and a proportion of that of the chair must be supported by the attendant's hands in wheelchair manoeuvring. The forces exerted on the attendant's hands, wrists and arms are substantial, and must be maintained by the muscle configurations associated with this part of the body, which are not the most suitable for weight bearing. (Edholm, 1967)

6.5.4. Wheel configurations of attendant propelled wheelchairs

There are two basic configurations used with attendant propelled wheelchairs, firstly there is the four fixed wheel configuration which is characteristic of purpose-built attendant chairs, and secondly the front castor, large rear wheel layout, discussed previously, which is the common configuration for many user propelled wheelchairs.

6.5.4.1. Four wheeled fixed position configuration

The choice of a four wheeled fixed position configuration is specified for many purpose-built attendant wheelchairs because of the simplicity of its operation and reliability of performance. Used out of doors on surfaces that would pose problems of stability for castor wheels, the fixed position of the four wheeled system offers a smooth, vibration reduced ride for the wheelchair occupant, particularly when fitted with wheels larger in diameter than the normal range allowed by front castoring. Where common axles are fitted to support the chair's wheels in pairs, springing is possible in addition to the specification
of pneumatic tyres, to enhance the quality of wheelchair ride.

The main disadvantage with a fixed wheel pattern is that of chair tilt rather than castor wheel manoeuvrability. (Nichols, 1971) To enable the function of wheelchair tilt to be achieved easily, two features must be included in the design specification of the wheelchair, both of which relate to the chair and occupant's resultant centre of gravity.

To facilitate voluntary wheelchair tilt, the resultant centre of gravity must lie in close proximity to the point of pivot, and the mechanical advantage offered by the wheelchair handle must be made greater than that of castored wheelchairs by an increased handle length. These factors pose two problems which must be taken into account, those of involuntary wheelchair tip due to the shift in the centre of gravity, and the effect of increased volume on mobility. (Cunniffe, 1970)

6.6. Motorized wheelchairs

Of the 36,980 wheelchairs issued by the DHSS in 1967, 604 were electrically powered. (BMA Planning Report No. 2, 1969) Designed or adapted solely for indoor use, the wheelchairs are prescribed on criteria that include not only the physical condition of the prospective user, but also his home environment. "The criteria of entitlement imply an assessment not only of the patient's physical disability, but also of his domestic environment. It is no use providing a powered indoor chair, if there is no suitable place to use it. Many small cottages or terraced houses are of such a design that a powered indoor chair would
not confer any additional independence. In order to obtain one of these chairs, the patient is not only subjected to a rigorous medical examination, but technical officers have to make a practical assessment of the domestic situation. The two aspects must be carefully balanced, for even a limited degree of independent mobility can restore self-respect, and sometimes the provision of a powered indoor chair can be the beginning of a chain of events leading to a comprehensive revival of activity for severely disabled patients.

It is sometimes difficult to assess the need and the effect of such a provision. Some patients do not strictly qualify because they are still able to propel themselves for short distances. But not infrequently a patient may be able to propel himself, yet in doing so may physically exhaust himself to such an extent that he is unable to achieve any useful activity other than propelling from one place to another. Furthermore, at centres, institutions, or schools for the disabled, or indeed at work, the distances or slopes involved are such that the patient cannot achieve the necessary mobility to traverse them. An electrically-powered indoor chair may be the means whereby the patient can achieve education or may continue at work. In such circumstances, a detailed assessment in the context of the home surroundings can lead to a correct solution of the problem".

(Nichols, 1971)

The prescription of DHSS wheelchairs, including motorized wheelchairs, is the responsibility of individual consultants,
and the following has been recorded: "In theory, wheelchairs are prescribed by consultants, but in practice few consultants have studied this problem adequately and the responsibility is often passed on to social workers or appliance clerks who have not been trained to do this work. Part of the fault stems from gaps in the doctor's education, particularly at a post-graduate level, but the situation could be improved by delegating the responsibility to physiotherapists or occupational therapists specially trained to assess patients and their wheelchair needs". (BMA Planning Report No. 2, 1969)

The importance of evaluation criteria in relation to prescription is reflected in the following: "About 30,000 new wheelchairs are issued by the DHSS each year, but experience indicates that at least one-third of these are returned, or not used, because they are unsuitable for the patient". (Nichols, 1971)

Given that the criteria of prescription includes both physical and environmental factors that will limit substantially the range of prescription, the number of motorized wheelchairs supplied (1,700 by 1970) bears little relationship to the number of users unable to propel themselves: "A very small proportion (about 1%) of the chairs are electrically powered, the rest are either self propelled (about one third) or need to be pushed (about two thirds)". (Harris, 1971)

In accepting that stringent limitations are imposed on the prescription of motorized wheelchairs, the relationship of
1% prescription to 66% potential requirement suggests that the correlation of the wheelchair's provisions with the characteristics of its user is not ideal. Because a large percentage of motorized wheelchairs are adapted from manually propelled ones by modifications that leave the wheelchair's body support features intact, one area of the wheelchair's function that warrants investigation is that of wheelchair control.

6.6.1. Design of control mechanisms

Because of the economics of providing a disabled individual with a motorized wheelchair, e.g. £150-£200 (Harris, 1971), and the stringent qualifying requirements, the type of users to whom motorized chairs are currently prescribed tend to be those who have substantially reduced physical capacity or disabilities involving body deformation etc. which preclude adequate limb co-ordination. The consequences of these factors often result in the necessity for individually designed or modified control units for motorized wheelchairs. Internationally, the range of control units recommended for this type of user has included wheelchairs controlled by the user's eyes, voice, mouth suction, and most other body features that can be controlled. (Lowman and Klinger, 1969)

Of this range, by far the most common types of systems used are those based on hand manipulation of the wheelchair's control(s). Of the hand control systems, three form the basis of most units, and can be discussed as micro-switch, T bar and tiller control.
6.6.1.1. Micro-switch control units

This type of control takes the form of micro-switch connections located radially about a small joystick positioned adjacent to the armrest supported hand of the user. By moving the joystick in the direction of intended wheelchair motion, the user can complete an electrical circuit which operates one or both of the power driven wheels of his chair. Complemented by additional switches, the system can offer a choice of speeds, and includes reverse. Steering is achieved by actuating one power driven wheel which produces in conjunction with the wheelchair's castor wheels a controlled change of direction.

6.6.1.2. T bar control

This system of wheelchair control operates directly on the front wheel of the motorized chair. Forming an extension of an integrated supplementary power unit in the conversion of manual to power driven wheelchairs, the T bar control projects upwards to locate between the knees of the user. Manoeuvrability of the wheelchair is achieved by radial displacement of the lateral bar which transmits its radial movement to the power unit directly below. This unit includes the traction wheels which provide the chair with powered motion and replaces the function of the existing castor wheels by raising the front of the chair slightly. The forward speed of the wheelchair and its reverse is controlled by hand lever or twist grip mechanisms integral with the T bar.

6.6.1.3. Tiller control

This method of wheelchair control is similar to that of the T bar
system in that it controls directly the position of the steering wheel(s). Mounted centrally between the knees of the wheelchair occupant, it can operate the radial displacement of a power unit, or, mounted adjacent to an armrest, it can control the steering wheel position through a linkage.

6.6.2. Limiting factors of use

Although widely specified for use with different types of motorized wheelchairs, limiting factors of the specification of the three methods of wheelchair control do exist, and consideration will be required in the relationship of these limitations with the sex and disability of the proposed user.

6.6.2.1. Sex of user

With centrally mounted control mechanisms that locate between the knees of the user, problems do exist with female users, particularly in the area of choice of clothing (Kamenetz, 1969) and possibly in the area of incontinence appliances.

6.6.2.2. Disability of user

Two of the disabilities that can be substantially affected by the type of control system fitted to a wheelchair are arthritis and spasticity. This is due to the response of the chair's electric motors to battery power output in starting the chair from rest. The resulting jerk can be painful, particularly to acutely inflamed joints, and can trigger involuntary motions in some spastic patients. (Kamenetz, 1969)

Where reduced arm function and strength form part of the
disability of the wheelchair user, any operation such as removal of a control mechanism as in the case of the T bar can present difficulties, particularly with independent wheelchair transfer. The factor of arm strength and limited function can also influence the effectiveness of tiller control, especially in determining the direction of motion of a stationary chair.

6.6.3. Battery maintenance
The range of an electric wheelchair and the requirement of battery charging will be dependent on a number of factors including user weight, environment, and scope of wheelchair use. However, it is common practice for many wheelchair batteries to be recharged overnight, and to enable this to take place conveniently, consideration must be given to the method of charger connection and the convenience of its use. Unless for example a connection can be made between the battery and charger by a weakened or arthritic hand, the independence of the user is diminished. To ensure that minimum difficulty is experienced with battery recharging, the connection between the wheelchair and the charger should be within visual seated arm range of the user, and the connection components should be of a size and configuration that allow positive manipulation.

6.7. Transportation of wheelchairs
Unless a wheelchair can be easily and conveniently transported, the range of its user's mobility will be dependent on the endurance of himself or his attendant, or on the power output
of the chair's batteries. In terms of transportability, two factors related to wheelchair design are of great importance: the size of the wheelchair, and its weight.

6.7.1. Size of wheelchair

The one factor that has influenced more than any other the present concept of the wheelchair is the motor car. Until 1914, the provisions of most wheelchairs were those of a chair on wheels with the associated limitations imposed by its non-collapsible structure. With the advent of personal transport on the form of the motor car, an extension of the independence of the disabled was recognized, and a wheelchair capable of easier transportation developed. The concept of this wheelchair in association with the influence of the bicycle-wheel forms the basis of design on which many current wheelchairs are modelled. (Kamenetz, 1969)

However, technical developments, and a much wider range of prescription have since that time resulted in more complex wheelchairs that require greater consideration in the aspect of transportation if the full potential of their users is to be realised. With reference only to the size of the wheelchair, there are two ways in which its transportation can be made easier: one is to increase the volume of space available for transporting the wheelchair, and the other is to reduce temporarily the size of the wheelchair. Both methods have their limitations as well as advantages, and these are discussed below.
6.7.1.1 Transportation space

The limitations imposed on the advantages of increased transportation space are mainly those of economics. To secure increased space for the transportation of a wheelchair, it is necessary to consider a vehicle larger than those models making up the most popular and economic range. The consequences of a reduced choice in association with the requirement of increased space imply greater initial financial outlay to secure a suitable vehicle, and higher running and maintenance costs.

6.7.1.2 Wheelchair size reduction

The limitations on the amount of wheelchair size reduction possible will be dependent on a number of factors including the type of wheelchair, i.e. manual, attendant or motorized, the cost of including size reduction features in the design of the chair, and their reliability. With current wheelchair design, little can be done apart from the removal of accessories such as footrests, armrests etc. to reduce substantially the overall size of the wheelchair as the limitations imposed by the techniques of construction invariably affect only one of the wheelchair's dimensions, i.e. height, width or length, when folded.

In a recent study of the characteristics and requirements of wheelchair users (Platts, 1971) the following was recorded: "...86% complained that their wheelchairs could not be folded small enough for travelling by bus, car or tricycle and were generally bulky and cumbersome when folded. These were said
to be the reasons why travelling was restricted. Twenty-one percent said that the rigid position of the pushing handles was the main cause of difficulty when stowing the folded wheelchairs. Fourteen percent said that they found folding their wheelchairs a difficult operation to do and 4% said a requirement for a rigid seat meant their wheelchairs could not be folded".

6.7.2. Wheelchair weight

Depending on the type of wheelchair, the influence of its weight on transportation will vary. In the case of self propelled wheelchairs, the factor of weight can be of extreme importance in determining the ability of its user to maintain independent transportation. To enhance the possibility of this, lightweight aluminium wheelchairs are often recommended. These weigh considerably less than the more robust standard wheelchairs. (Kamenetz, 1969). With other types of wheelchair such as the attendant and motorized chairs, the factor of wheelchair weight is of slightly less importance in that the user would not be required himself to manipulate the wheelchair in transportation. However, even with less stringent criteria in respect of wheelchair weight, its importance must be given consideration, as many attendants are elderly. (Harris, 1971)

Because of factors associated with the economics of manufacture, it is often difficult to reduce substantially the overall weight of a wheelchair by design specification, and it becomes necessary to consider other methods of weight reduction for transportation.
One alternative method used with many models of wheelchair is chair breakdown. With the majority of current wheelchairs, this extends to the removal of armrests, footrests, batteries etc., but rarely includes any breakdown of the most substantial item, the wheelchair frame structure, including the wheels.

The main reason for this limitation lies in the engineering principles used in frame design, which rely on permanent frame connection for strength and flexibility. To offer the facility of further wheelchair breakdown for more convenient transportation, it is thought necessary to consider other methods of wheelchair frame construction, possibly based on the modular system of fabrication.
This section is concerned with the specification, fabrication and testing of equipment designed according to the recommendations contained in the previous two sections. While it is not possible to satisfy all the conditions specified above, every attempt was made to achieve the highest common denominator, and to test the validity of the design solutions proposed.
CHAPTER 7

The Project Wheelchair

7.1. Introduction

In order to test the quality of the project's research and the effectiveness of the recommendations produced, it was considered essential to translate as much of the work as possible into a form which could be evaluated. This was achieved by the production of a wheelchair to satisfy the requirements of a selected group of wheelchair users.

7.2. Selection of disability group

Because of the extremely wide range of disabilities that exists within the total wheelchair population, the specification of one wheelchair to satisfy all the varying user requirements is not possible. What is possible, however, is the selection from the total wheelchair population of a group of users whose characteristics and requirements are sufficiently similar for realistic design parameters to be established.

By relating a wheelchair's design to the requirements of one section of the total wheelchair population, it is thought that a higher level of correlation between the provisions of the wheelchair and the requirements of its proposed users is possible. It is thought that this concept offers an additional advantage in that by reducing the range of disabilities to be accommodated for within the design of the chair, the range of variables to be considered in the testing of the wheelchair can be reduced to a manageable and meaningful level. Also, providing the wheelchair is found to be acceptable, the possibility can be
created whereby through adaptation of the original design an extension in the range of prescription can be made without the necessity of a totally different wheelchair. The group selected as representing the largest cross section of factors to be satisfied in a wheelchair's design was that presently accommodated for by the DHSS Model 8. This is a standard adult model self-propelling wheelchair which has rear located propelling wheels.

7.3. Recommendations used in project wheelchair

**Seat**

**Width:** The minimum width of seat to fit all but the broadest individual is 16" (Branton, 1966)

**Depth:** A depth of 15" is usually recommended. This will accommodate over 90% of able men and women (Branton, 1966)

**Shape:** Concaved to profile approximately with user's buttocks, and must not be subject to deformation under sitting pressure

**Angle:** 5 degrees downward slope from seat front, measured from the horizontal

**Upholstery**

**Material:** Permeable material that can be wiped or laundered for cover, i.e. natural fabrics or gluteraldehyde treated sheepskins

**Surface tension:** The material should be free to accommodate seated pressure without shear stress being set up, and without creasing with prolonged use
Seat (Continued)

Core material: This should be made up of a resilient material that offers firm support from a thickness less than 2", and the material must be protected from moisture infiltration.

Backrest

Height: The height of the backrest should fall below the level of the user's scapulae, approx. 16".

Width: The width of the backrest should not exceed the width of the user's chest, thereby frustrating arm mobility. Suggested width at top 15" (Brattgard, 1969).

Shape: Laterally concaved to equate approximately with the profile of the user's back, and should offer support under load without deformation.

Angle: An included angle of between 95° and 110° measured from the seat surface, and accommodating for the 5° lumbar curve (Branton, 1966).

Upholstery: As for seat, with the exception of core material thickness, which should be approx. 1 inch thick.

Armrests

Height: 9" measured from depressed seat.

Width: 19" measured across seat.

Length: To suit user requirement, i.e. full, angle or desk etc.
**Armrests** (Continued)

**Upholstery:** Upholstered with permeable material and padded to protect the user's ulnar nerve. The upholstery to be such the user handgrip can be achieved and maintained, i.e. section profile based on a diameter of $1\frac{1}{4}'' - 2''$

**Other features:** The armrests must be removable or have the facility of swing to allow wheelchair transfer, and must lock securely when in use.

**Legrests**

**Length:** Legrests must be adjustable in length from a 16" - 17" minimum to an extended length of plus 6" measured from the top surface of the leading edge of the seat.

**Angle:** The angle of the legrests must be adjustable over a range sufficient to accommodate fixed knee configurations and to aid venous return from the user's legs. Range of leg elevation equals $90^\circ$

**Other features:** The legrest(s) must be detachable or have the facility of swing to aid wheelchair transfer.

**Footrests**

**Size:** The size of footrests should be sufficient to ensure that no point loading of the user's feet occurs.

**Foot retention:** If possible, the design of the footrest should include features that maintain foot contact during leg spasm.
Footrests (Continued)

Other features: The footrest in conjunction with the legrests must be detachable for transfer, or have the facility of swing.

Centre of gravity

Adjustment: The wheelchair should include the feature of centre of gravity adjustment so that variations in the resultant centre of gravity of the wheelchair and its user can be accommodated for.

Wheels

Configuration: Four wheel configuration with two large (22" - 24") propelling wheels mounted at the rear of the wheelchair, and two small (8") castor wheels mounted at the front.

Tyres: Pneumatic or solid to suit the requirements of the user and the environment.

Handrims: Maximum overall handrim diameter to be 2" less than wheel plus tyre diameter. Section diameter of handrim equals 3/4".

Brakes: Two independent brakes, each to operate on one propelling wheel to give both positive lock and friction resistance to the wheels. Both systems must be adjustable for pressure application, and should be located within easy reach of the wheelchair user.
Propelling handles

Split wheelbarrow type pushing handles to be fitted to the wheelchair, adjustable in height to 39", and spaced approximately 19\(\frac{1}{2}\)" apart.

Handgrip length to be a minimum of 5", and its section to relate to a diameter range of \(\frac{3}{4}\)" - 1\(\frac{1}{2}\)"

The angle of presentation of the handgrip to the attendant is recommended as \(-10^\circ\) to \(-20^\circ\) measured from the horizontal

Foot tip bars

Two wheelchair tip bars are to be included in the wheelchair's design, located one to each side of the chair. The attendant foot contact area of the tip bars to be such that no point loading of the foot occurs

Wheelchair size

The overall size of the wheelchair will be the product of a number of factors including wheel size, seat height and legrest length etc.

Ideally a wheelchair should be as small as possible, while still satisfying the demands made on it, in order to ensure maximum manoeuvrability and ease of transportation. However, of the dimensions involved, the most important is wheelchair width, and it is of paramount importance that every effort is made to keep this size as small as possible to facilitate the wheelchair's passage through doorways.
Wheelchair weight

The weight of a wheelchair is of great importance particularly if it is to be lifted in transportation by the user, e.g. use with a car. It should therefore be kept as low as the economics of manufacture and prescription allow.

7.4. The design and manufacture of the prototype wheelchair

Having produced the list of specifications necessary for the creation of a wheelchair to satisfy the requirements of a defined group of users, the object was then to translate these specifications into a wheelchair that could be manufactured. This was achieved by an approach to a large international company, Hille International Ltd., who specialise in the manufacture of office and domestic furniture. There were many reasons for the choice of this company, the main one being that they have available a range of domestic and office chairs the body contact sections of which have been designed to include the recommendations of the BS 3893. In addition to this factor of ergonomic related design was that of subjective test data (Shackel et al., 1969), and the fact that many millions of the chairs were in use throughout the world. (Personal communication, Julius)

Given that a selection from this range of chair shells would satisfy the specifications made, the additional advantages to be gained from an association with the company were thought to be modern design and the techniques of highly competitive commercial manufacture. The negotiations that ensued from the
initial approach to the Company resulted in an undertaking by them to produce a prototype wheelchair to the specifications made. This was achieved in conjunction with the Company's consultant designer who assumed responsibility for the aesthetic styling of the chair, and for its techniques of manufacture.

The quality of the relationship that existed between the skills concerned at this stage of the wheelchair's development cannot be stressed too highly, and it was possible through the combination of the disciplines of design, engineering and ergonomics to finalise the wheelchair's working drawings without serious difficulties. On completion of the working drawings, the fabrication of the prototype wheelchair began, using as far as possible the materials and manufacturing techniques that would be desirable for large-scale production of the wheelchair.

The advantages associated with this type of prototype fabrication are those that indicate the possible future cost of large-scale manufacture in terms of skills required and economics involved. Any limitations on this system of manufacture are usually related to finding temporary substitute methods of parts manufacture necessary to maintain the cost of the prototype within an acceptable budget.

Although the specifications used in the design of the wheelchair relate to the requirements of one particular group of users, the concept of the wheelchair's design was that an extension of its prescription could be possible, through adaptation, provided the initial design was receptive to this. By designing the
wheelchair as a modular structure, it was considered that this possibility would be enhanced in that varying sections of the wheelchair could be cheaply and easily replaced with ones more compatible with the requirements of other users.

From Figures 11 to 13, it will be seen that the construction of the wheelchair is based on a central beam which carries two folding parallelogram mechanisms which support the wheel beams. The use of this central beam as a nucleus of the chair's design establishes a datum from which changes in the chair's body support surfaces can be made, as well as wheel patterns and chair width.

7.4.1. Changes in body support surfaces
Although designed with a particular seat shell in mind, the simple mechanism of shell connection to the central beam enables the wheelchair to accept possible alternatives to this, providing the seat subframe is included. Other support surfaces such as armrests and footrests can be easily changed for others of different configuration without affecting the strength or stability of the wheelchair.

7.4.2. Wheel patterns
The feature of mounting the wheelchair's wheels on beams allows not only adjustment of the chair's centre of gravity, but also a possible reversal of the driving wheels to the front of the wheelchair. It also facilitates the use of smaller wheel sizes by the replacement of the present beams with others which relate to smaller wheels.
Fig. 11. Seat unit attachment

Fig. 12. Folded parallelogram mechanism and seat unit

Fig. 13. Extended parallelogram mechanism and seat unit
7.4.3. Changes in wheelchair width

The parallelogram mechanism used to collapse the wheelchair laterally for transportation etc. has an additional feature in that it lends itself almost ideally to a system of wheelchair width control. This would be achieved if required by the introduction of adjustment screws operating on the end sections of the parallelograms. The combination of possibilities of adjustment and/or replacement offered by the wheelchair's design is thought to be particularly desirable where changes in user stature is a factor to be accommodated.

7.4.4. Wheelchair design and weight factor

The design of a wheelchair quite obviously controls the factor of its weight, not only in terms of materials and their amounts, but also in the way in which the materials are applied. Given direct and simple loading of a block of material, calculations of tensile, compressive and shear stress can be made quite easily, as well as the bending moments applied. In the case of a dynamic structure such as the wheelchair, the determination of stress factors etc. are not so easily made, particularly when it is appreciated that even minor shock loading of a beam under stress can produce a substantial increase in the stresses applied to it.

To accommodate for factors such as shock loading of the wheelchair, its strength must be substantially increased above the level of a static structure directly loaded with the same weight. This increase above the point of support is referred to as the factor of safety, and for a wheelchair it must be as high as the associated aspects of design, such as weight etc., will allow.
The easiest way to overcome the factor of safety situation is with the specification of high tensile alloys. However, these are both expensive to produce, and often difficult to work, particularly with a machine intensive system of manufacture. The alternative to this, which is commonly applied, is to use an amalgam of materials, the properties and characteristics of which can be equated with the estimated stresses (plus the factor of safety) to which the structure will be subjected.

In the case of the project wheelchair, the main materials used were:

1. aluminium alloys
2. high tensile steel
3. high quality mild steel

Where high tensile stresses were calculated and dimensions of component parts had to be kept small, high tensile steel was used. For wheelchair parts involving compressive stress and where size was not so important, aluminium alloys were used, leaving the use of mild steel in areas of moderate stress. The use of materials in this way allowed the fabrication of a wheelchair which was considered to offer a balance of the factors of strength, weight and economics.

7.4.5. Wheelchair design and transportation

Accepting the control exercised by the economics of manufacture and the type of materials used in the construction of the wheelchair, the contribution of the designer in ensuring the easy transportation of the chair lies in the relationship of the
design features of the chair to the difficulties associated with wheelchair transportation. These difficulties invariably include the factors of wheelchair size and weight. As previously discussed, limitations exist to the overall reduction of both wheelchair size and weight. Given these limitations, the only reasonable alternative the designer has to ensure convenient wheelchair transportation is to break the wheelchair down into sections. In the case of the project wheelchair, this feature was achieved quite easily in that a natural division of weight occurred with the separation of the seat and backrest unit from the central support beam. By associating other wheelchair components such as handles, armrests and subframe with the seat unit, the overall weight of the wheelchair could be divided easily in the approximate ratio of six parts and four parts of the total ten parts. As most current wheelchair have the provision of a 5-component breakdown with a less favourable weight breakdown ratio, it was considered that a reasonable compromise of all the factors involved had been achieved.

7.5. Viability of the wheelchair for large-scale manufacture

The conclusion to any project which seeks to satisfy the requirements of a group of individuals through a product or piece of equipment must involve a product evaluation programme, the standard of which is in proportion to the consequences of its failure in use.

To enable the wheelchair to be evaluated and tested at the highest possible level, an invitation from the DHSS was taken up, on completion of the first prototype (see Figs 14 - 21)
Figs. 14 to 16.

Project wheelchair

Fig. 14

Fig. 15

Fig. 16
Fig. 17. Rear view of project wheelchair

Fig. 18. Stowed armrests
Fig. 20. Armrest in transfer position

Fig. 21. Extended and angled legrest
to present the wheelchair for examination. As a result of this,
examination and subsequent consultation with Hille International
Ltd., the decision was taken for a test batch of wheelchairs to
be manufactured, and evaluation programmes to be constructed and
applied.
8. Wheelchair test programmes

8.1. Human factors testing

Although there are accepted procedures for the ergonomic testing of consumer goods in terms of their ease and comfort of use, and safety and reliability of operation, it is no easy matter to transfer these procedures to the testing of wheelchairs, in that the principles laid down (Kirk and Ridgway, 1970) postulate a series of consecutive actions, each of which can be defined, and which lead to a finite end result. With wheelchair use, there is no series of consecutive actions, nor is there any finite end result, and so while the principles of rating and its analysis can be followed, other principles cannot. The greatest difficulty is a temporal one: the temporal span of wheelchair occupancy and use may well run to years, but a testing programme cannot hope to do the same.

The temporal difficulty also appears internally in any testing programme: sitting in a wheelchair cannot be assessed and rated in the same way as, for instance, removing an armrest. Nor can the same criteria of ease and comfort be applied for a state, a prolonged action and an immediate action. It is also difficult to assess the length of time needed, or the frequency of repetition, for an assessment to be made at all, and whatever time limit is placed, it is certain that some types of activity will be excluded.

It is also true to say that testing any article in isolation
will produce dubious results: it will be impossible to tell from the results whether a single article functions as well as it might without some comparative basis present. And of course, if two articles are to be compared, the testing procedures must be as nearly comparable as possible. Thus, solutions must be found to two problems: firstly, the design of the testing method, and secondly, the application of the test. A third problem, that of subjects for the testing programme, will be discussed later.

8.1.1. Testing method

There are a number of methods available for the testing of consumer products (Kirk and Ridgway, 1971), and of those available, the one chosen as offering the greatest possibility of obtaining information about wheelchairs was a combination of observation and questionnaire application. The combination is important, as some aspects of wheelchair use will be obvious and visible, whereas others, particularly dealing with long-term sitting comfort, or accidents that have already happened, will only yield to questionnaire application.

Thus, a questionnaire was devised that fell into four parts. Part 1 deals with the body support surfaces, the seat, backrest, armrests and footrests, requiring information about the suitability of their various characteristics such as height, width, angle, surface and so forth, as well as as overall comfort rating on each. Part 2 deals with the handling of parts of the wheelchair, with questions on the overall ease, comfort
and safety of use of the armrests, foot and legrests and brakes, and these operations were observed. Part 3 concerns the use of the wheelchair, and is divided into two sections, the first dealing with the use of the wheelchair by its occupant, and the second with the use of the wheelchair by an attendant. Use of the wheelchair includes transfer to and from the wheelchair, propulsion, folding and unfolding, transportation in a motor vehicle, pushing and tipping.

Part 4 of the questionnaire includes general questions about the wheelchair relating to accidents, damage, reliability, appearance and overall assessment of the wheelchair.

8.1.2. Pilot run

In order to test the suitability of the questionnaire for general application, six subjects were selected and the questionnaire applied. The subjects were selected on the following basis:

1. Extensive users of their wheelchairs
2. Car owners: three owner-drivers, and three driven by the attendant
3. Living in a family group so that the section dealing with the use of the wheelchair by an attendant could be completed.
4. Of an educational background such that the purpose of the pilot run could be made clear, and reliance placed on the resulting comments.

The questionnaire was applied to establish:

1. that all the questions were phrased in such a way as
to mean the same to the subject and the observer.

2. that all the questions were capable of being answered.

3. that the subject was of the opinion that no further general questions would have covered a point he wished to raise.

8.1.2.1. Results

1. No question was found to cause confusion in the way it was phrased.

2. While not all the questions produced a response from each subject, particularly in terms of the "Any further comments" questions, or where the user did not attempt the activity in question, all questions were found capable of generating a relevant response.

3. Suggestions from the subjects as to further questions which might be included were as follows:
   a) maintenance of the wheelchair
   b) difficulty of obtaining spare parts
   c) necessity for greasing the chair, and transfer of grease to clothing
   d) difficulty of certain activities such as dressing in the wheelchair, and carrying personal belongings.

As no comparison with the project wheelchair could be made on the first three items, it was decided that although they were important they could not reasonably be included in a comparative evaluation of two wheelchairs, one of which was still in the prototype stage. The fourth item was also excluded, as it represented activities which were not wheelchair-specific.
The single factor which did emerge was that the tenses of the verbs were not always consistent, so with this point corrected, the questionnaire was considered suitable for general application. (see Appendix 1)

8.1.3. Selection of subjects

It is obviously of great importance when testing a piece of equipment for use by the disabled to obtain subjects who are representative of the range of users for whom the equipment is designed. However, even given the overall category of people who use a manually propelled wheelchair, there is extreme difficulty in establishing a meaningful range either in terms of a detailed clinical assessment or in terms of remaining function. "Factors affecting the degree of physical impairment are loss of muscle power and sensation, leading to decreased strength and loss of co-ordination and endurance. The presence of spasticity, tremor, stiffness, pain and fatigue may or may not limit the individual's competence according to severity. Competence will also be affected by self-confidence, intellectual capacity and motivation, indicating that the physical and psychological factors are very closely linked.

Although these factors individually and collectively may indicate the degree of disability, the severity of each factor tends to increase the over-all severity of the patient's disability, and any one factor may have an overriding influence". (Goble and Nichols, 1971)

The use of classical clinical signs and observations, while
of vital importance in individual terms, gives little information in terms of inter-subject comparison and the formation of a range of categories of users which could be used for a representative selection of subjects to be made.

Several methods of functional assessment were examined to discover whether they might have a possible application, but none was found to be helpful in the context in which it was needed.

Given this intractable problem, certain decisions had to be made. Firstly, as the project wheelchair was to be evaluated against an existing wheelchair, in that it is extremely difficult to evaluate any article in isolation, the following factors ensued:

1. As the project wheelchair in its existing form was designed as a standard wheelchair from which modifications could later be made, it should be evaluated against a standard, adult, self-propelling wheelchair. At the request of the DHSS, the standard wheelchair chosen was the DHSS model 8L.

2. To ensure that users were not so recently disabled as to make it necessary to learn how to handle two different wheelchairs in a very short space of time, it was decided that only subjects who had owned a wheelchair for a minimum of six months should be approached.

3. So that subjects were not put at risk, it was decided to exclude any person particularly at risk in terms of
pressure sores or any other medical condition considered by his clinician as potentially or actually a threat to the physical state of the individual. This also included the frail, elderly individual.

4. Because of the method used for evaluation, that is, questionnaire and observation, it was decided to exclude individuals with severe hearing or speech impediments because of the difficulties involved in questionnaire presentation to such individuals.

5. All subjects must voluntarily agree to take part in the trials.

Given these limitations on the choice of subjects, one method presented itself as offering possibilities, and that was to take all users of the DHSS model 8L wheelchair (with the exceptions mentioned above excluded) from a given prescription centre, and approach them for their consent to take part in the trials.

8.1.3.1. Number of subjects

The minimum number of subjects required, in view of the amount of time available for testing, and the number of prototypes (six) was thirty-six. While it is fully realised that this is a minimum number, the wheelchair was being tested as a standard chair, without any of the individual modifications which can be made to increase its range of suitability, and it was therefore decided that this number of subjects would be sufficient to establish its value as a base-line.
The subjects were first approached for their consent through the prescription centre. In all, 81 subjects were approached, these being all those who had been issued with an 8L wheelchair from the prescription centre and had owned a wheelchair for six months. The responses were as follows:

- Subject had died: 13
- In hospital: 3
- Left the district: 2
- Declined to take part: 9
- No reply: 10

The non-responses were taken to mean that the subject did not wish to take part in the evaluation programme, and thus a possible total of 44 subjects remained willing to take part.

These 44 subjects were all visited, and the purpose and method of the test programme explained. As a result of the visits, four subjects were excluded, three because of ill-health at the time of the visit, and one who had very recently been issued with an attendant-propelled chair and was therefore unable to take part in the programme. Thus, 40 subjects were available for the test programme.

8.1.4. Application of test programme

Having written and tested the questionnaire, and selected the subjects to take part in the test programme, the application of the test began. In order to achieve similarity of conditions
of testing for both the model 8L and the prototype wheelchair, the following procedure was observed.

8.1.4.1. First visit

On this initial visit, the purpose and method of the programme were explained, and the subjects given an assurance of anonymity. The subjects were then given a list of topics (see Appendix 2) on which questions would subsequently be asked. (It was during this series of initial visits that four of the 44 subjects visited were excluded). The subjects were asked to use their wheelchair normally during the following days, but to give consideration to the list of topics about which questions would be asked.

8.1.4.2. Second visit

Six days later, the subject was again visited, and the questionnaire applied. For the first section of the questionnaire, concerning the support surfaces of the wheelchair, the subjects were requested to limit their observations to their experiences since the first visit, in order that a similarity of test procedure of both wheelchairs could be achieved. For the second section of the questionnaire, dealing with the handling of the armrests, foot and legrests and brakes, the operations were observed by the interviewer. If the operation (for instance, removal of armrests) had never been attempted, either because it was not necessary or because the subject's disability was such that the operation was out of the question, it was coded Not Applicable. If the subject had attempted the operation and
found it beyond his capacity, it was coded Impossible, and the reasons elicited.

All other questions on the use of the wheelchair and the general questions in the fourth section of the questionnaire were limited to the subject's experiences since the first visit, except in the following case. Where subjects mentioned accidents occurring prior to the first visit and as a result specifically of the wheelchair's design, note was made of this, with the approximate date of the accident. For instance, one subject had had to spend three months in hospital as a result of falling on a protruding armrest tube: another had been stabbed by a heel loop retention peg when falling out of his wheelchair, and it was considered important that these facts be recorded, even though they would not be used in the comparison of the two wheelchairs.

When the questionnaire had been completed by the interviewer who put the questions verbally to the subject and recorded the responses, the questionnaire was handed to the subjects for their inspection. The subjects were requested to sign the questionnaire as reflecting accurately their experience and opinion. In two instances this signature could not be obtained because the subjects were registered blind, but it was considered of the greatest importance to obtain the signature wherever possible so that the accuracy of the responses was not in doubt.
8.2. Supply of prototypes

On completion of the first series of visits to the subjects, it had been planned that an interval of three weeks was to be observed before the delivery of the prototype wheelchair to the subjects. This was to ensure that a sufficient period of time had elapsed for subjects to answer the questionnaire concerning the prototype wheelchair without specific reference to their responses to the first questionnaire.

However, as the proposed date of delivery of the prototypes approached, it became apparent that the company concerned with their manufacture, Hille International Ltd., could not meet the delivery date. This was due to the aftermath of the industrial three-day week. Faced with the difficulties involved in securing the prototype wheelchairs within the finite period of the research project, only one feasible alternative was available. This was to build at the University the six prototype wheelchairs required for the human factors testing programme. The wheelchairs were built with the co-operation of the Department of Transport Technology, and were produced over a period of one month by the author and the consultant designer associated with the project.

The time taken to build the wheelchairs necessary to the project's conclusion meant that adjustments had to be made to the remainder of the human factors test programme. The consequences of these alterations were twofold: firstly, it meant that the time period between the application of the two questionnaires was increased by approximately one month, and secondly, the time allowed for subject use of the prototype wheelchairs had to be reduced to
three days. With regard to the first consequence, this was considered to have little or no effect, other than to reduce further any contamination of questionnaire response. The second consequence was more significant in that it meant that strict parity of testing could not be observed. In terms of responses to the questionnaires, the sections where a fair comparison between the two wheelchairs could not be drawn would be those sections referring to accidents occurring during the week prior to the application of the questionnaires. For the other sections, the suitability of the support surfaces could, it was considered, be established by the user over a comparatively short period of time, and in the case of handling of parts of the wheelchair, these operations were instantaneous, and observed by the interviewer, so while not ideal, this state of affairs was considered to be acceptable, particularly in view of the fact that the subjects were experienced wheelchair users. While three days' use of the prototype wheelchair was less than had been envisaged, it was considered imperative that the wheelchairs were built and subjected to even a foreshortened evaluation programme, so that a judgment could be made on them.

There was a third consequence to the delay in securing the prototype wheelchairs for test, and that was that in the interval, two subjects had been admitted to hospital, and two had gone on holiday. Thus, thirty-six subjects took part in the evaluation programme.
8.3. Third visit

With the availability of the prototype wheelchairs, the test programme continued. The subjects were visited for the third time, and presented with the prototype wheelchair. A full explanation and demonstration of the wheelchair and its mechanisms were given, and the subjects asked to use the wheelchair normally during the following days. Each subject was given the same list of topics about which questions would be asked as previously, and also a form on which to record any occasion on which it was necessary to revert to his usual wheelchair (see Appendix 3).

8.3.1. Fourth visit

After three days, the subject was again visited, and the questionnaire applied as described in section 8.1.4.2. The subjects were again asked, where physically possible, to sign the questionnaire as reflecting accurately their responses. The forms concerning use of own wheelchair were collected, and the subjects were thanked for their co-operation in the test programme. The prototype wheelchairs were then removed, and examined for damage or mechanical fault before re-issue.

8.4. Data processing

With the completion of the 72 questionnaires, the information they contained was coded and transmitted where possible to data processing cards. Where a response was in the form of a comment, these were extracted to supplement and give context to the computer analysis. The system of analysis used was
that of paired comparison, to give a quantitative breakdown of the number of subjects preferring one chair over the other for each common question (see Appendix 4).

When the data had been extracted from the questionnaires, the page containing information about the subject was removed from each questionnaire and destroyed, so that subject anonymity was preserved.

8.5. Results and discussion

In the following sections, the analysis of questionnaire data is made in two ways. One is by giving frequency counts of ranked questions, and the other is in the discussion of the responses and relevant comments made. These comments were in response to questions not analysed in Appendix 4.

Also included in the discussion will be injury, and damage to property, although it should be appreciated that no fair comparison can be made of these specific responses due to the difference in time scaling of the test periods. However, while this information has no comparative value in this instance, it was considered that it did have an intrinsic value in that knowing the cause of injury or damage may help prevent them in the future.
8.5.1. Description of subjects

Of the 36 subjects, 25 were male and 11 female. The age range of the males was 20 - 73 years, and of the females 23 - 65 years. Five of the subjects were left handed, 31 right handed. The mean total time the subjects had used a wheelchair was 8 years (range 8 months to 24 years, and the mean time the subjects had used their present wheelchairs was approximately 3 years (range 6 months to 8 years).

The subjects' accommodation was as follows:

<table>
<thead>
<tr>
<th>Type of accommodation</th>
<th>No. of subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>2</td>
</tr>
<tr>
<td>Bungalow</td>
<td>4</td>
</tr>
<tr>
<td>Terraced house</td>
<td>2</td>
</tr>
<tr>
<td>Semi-detached house</td>
<td>11</td>
</tr>
<tr>
<td>Institution</td>
<td>17</td>
</tr>
</tbody>
</table>

Use of motor vehicles was as follows:

- Invalid three-wheeler      8
- Self-driven commercial vehicle 5
- Attendant driven vehicle 17

These figures are not mutually exclusive.

Four subjects never had an attendant to propel them, and three always had an attendant present, although only one never attempted self-propulsion. The remaining 29 subjects needed an attendant in varying degrees.
Distribution of disabilities was as follows:

<table>
<thead>
<tr>
<th>Disability</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Multiple sclerosis</td>
<td>11</td>
</tr>
<tr>
<td>Paraplegia (various causes)</td>
<td>7</td>
</tr>
<tr>
<td>Cerebral palsy</td>
<td>5</td>
</tr>
<tr>
<td>Arthritis (rheumatoid and osteo)</td>
<td>5</td>
</tr>
<tr>
<td>Stroke</td>
<td>3</td>
</tr>
<tr>
<td>Lower limb amputation</td>
<td>2</td>
</tr>
<tr>
<td>Spina bifida</td>
<td>1</td>
</tr>
<tr>
<td>Quadriplegia</td>
<td>1</td>
</tr>
<tr>
<td>Freidreich's ataxia</td>
<td>1</td>
</tr>
</tbody>
</table>

8.5.1.1. Use of own wheelchair

During the period of trial of the prototype wheelchair, six subjects reverted to their own wheelchairs, in the following instances:

1. Subject ran a sweet and cigarette shop, and needed a tray to carry his stock. He thus used his own chair for about 30 mins twice a day.

2. One subject used his own chair when he wished to go out in his car.

3. The remaining 4 subjects reverted to their own chairs after periods varying between 3 and 5 hours on each time they used the prototype chair because they found their own chair more comfortable.

8.5.1.2. Wheelchair replacement

In the three instances of mechanical breakdown of the prototype chair, the following decisions were made. On two occasions, the chair was immediately replaced, and the test period recommenced. On the third occasion, the chair was broken at the end of the test period, and the subject agreed that he had made sufficient use of the chair to form an opinion about it.
8.5.2. Design of wheelchair

a) The Seat (Questions 1 - 7)

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<thead>
<tr>
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<thead>
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<thead>
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Q6 (Comfort)

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<th>S</th>
<th>U</th>
<th>VU</th>
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<td>17</td>
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Discussion

There are two main topics for discussion arising from these results: seat depth, and seat upholstery. With regard to seat depth, it can be seen that the British Standard for seat depth is not sufficient to satisfy the requirements of a substantial proportion of the wheelchair users, and a seat depth of between 15" and 18" must be chosen according to the needs of the individual.

Concerning the level of upholstery offered, it will be seen from the results that the prototype chair fared slightly better than the 8L. This result is interesting in view of the fact that of the 36 subjects taking part, 25 used supplementary cushioning with the 8L wheelchair, varying in thickness from 1" to 4", whereas with the prototype chair an upholstery thickness of less than \(\frac{1}{2}\)" was provided, and in no case was extra cushioning used. The favourable comfort response to the prototype wheelchair was thought to be due to the contoured surface of the prototype wheelchair seat, and it is felt that had it been possible to comply with the recommendation of 2" cushioning, a higher level of seating comfort would have been achieved.
b) The Backrest (Questions 8 - 13)

<table>
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Q13 (Comfort) | Frequency count
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<td>Prototype</td>
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<td>11</td>
<td>7</td>
<td>10</td>
</tr>
</tbody>
</table>

**Discussion**

These results clearly reflect the conflict of interest between providing an adequate level of support for the back and creating an acceptable level of arm and scapula freedom necessary for wheelchair self-propulsion. In attempting to give the prototype wheelchair user unhindered arm mobility, it would appear that the level of long term sitting comfort was reduced for some types of wheelchair users, particularly those who have poor trunk stability. The range of backrest height would appear to be from a minimum of 13½" to a maximum of 17½", with the possibility of further support being provided by a headrest. The dimensions of the 8L wheelchair satisfied most subjects, but the angle and the contour were less acceptable. This could be attributed entirely to the slung canvas construction of the 8L wheelchair which sagged with use.
c) The Armrests (Questions 15 - 21)

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<td>Prototype</td>
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<td>Q18 (Distance apart)</td>
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<td>Q19 (Surface)</td>
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Q20 (Comfort)  

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<td>4</td>
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</table>

**Discussion**

Three subjects had permanently removed the armrests on the 8L wheelchair, as they preferred to operate the chair without them. However, all subjects used to armrests on the prototype wheelchair. From the results, there are three factors which warrant discussion, two associated with the 8L wheelchair, and one with the prototype. With regard to the 8L chair, these are armrest height, and armrest upholstery. Armrest height is a product of seat cushion thickness, and it was found that where supplementary cushioning had been used, the armrest height was satisfactory, but where no cushioning was present, the armrests were considered too high.

While the level of upholstery on the 8L wheelchair was found to be good, the comfort rating of the armrests was somewhat reduced due to the type of material used to cover the armrests. This was highly susceptible to cracking which produced sharp edges, causing some discomfort in use.

The outstanding criticism of the prototype wheelchair armrests was that of armrest length. In making a decision as to the length of the armrests, consideration was given to the close approach to furniture etc., and while the armrests satisfied this condition, they were found to be too short to be an aid to standing transfer, so a choice of armrest length should be made available.
d) Footrests (Questions 22 - 28)

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<th>Q22 (Length)</th>
<th>Frequency counts</th>
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<table>
<thead>
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<table>
<thead>
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Q27 (Comfort)  

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<th>VU</th>
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Discussion

Two subjects did not use the footrests on their 8L wheelchair, one having removed them permanently, the other using them only very rarely. No response was recorded to Q26 for one subject concerning the prototype wheelchair because the presentation of one of the subject's legs was such that the facility of control offered could not be used. As far as the 8L wheelchair is concerned, two important aspects emerged. One is the foreshortening of the footrest by the heel loop, and the other is the lack of foot restraint offered by the footrests. Of the 36 subjects, 19 commented that their feet fell off the footrests at frequent intervals.

The main criticism made of the prototype wheelchair footrests was that they were too narrow. While offering an adequate foot area support surface, the footrest width provided did not allow a sufficient platform for a variation in leg position. It was also suggested by a few subjects that the height of the foot retaining lip located on either side of the footrests should be raised an additional half-inch.
8.5.3. Handling of parts of the wheelchair

a) Armrests (Questions 29 - 40)

Q29 (Ease of removal)  
Frequency counts

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Q31 (Comfort of removal)  
Frequency counts

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Q33 (Ease of replacement)  
Frequency counts

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<th>D</th>
<th>VD</th>
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Q35 (Comfort of replacement)  
Frequency counts

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<td>9</td>
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<td>9</td>
<td>4</td>
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<td>0</td>
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</tr>
</tbody>
</table>

Discussion

It is very clear from the results that there was a marked difference between the two chairs in respect of removal and replacement of armrests. Where the difficulty lay with the operation of the 8L armrests was in the frequent jamming of the armrest tube location.
and in the fact that it was awkward to see and reach the rear armrest location tube.

With the prototype wheelchair, only one connection was necessary to locate the armrests, and because of the armrest swivel mechanism, this location was a simple matter. Favourable comments were also made in respect of the armrest locking mechanism, and also the fact that the armrests were permanently attached to the wheelchair.

Comment was made by six subjects on injuries they had received in connection with the armrests of the 8L prior to the test programme. Apart from one subject who fell on the exposed armrest tube, these injuries were associated with the removal of jammed armrests.
b) Legrests (Questions 41 - 62)

Questions 41 - 50 refer to the prototype wheelchair only.

Q41 (Ease of raising leg angle)
Frequency counts

<table>
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<th>D</th>
<th>VD</th>
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Q43 (Comfort of raising leg angle)
Frequency counts

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<th>U</th>
<th>VU</th>
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Q45 (Ease of lowering leg angle)
Frequency counts

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Q47 (Comfort of lowering leg angle)
Frequency counts

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<td>0</td>
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<td>2</td>
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</tbody>
</table>

Q49 (Accidents)

No accidents occurred.

Discussion

This feature of the wheelchair's design was very much liked, and could be operated easily and comfortably by almost all the subjects. It was found particularly useful by those subjects who stood to transfer, as the foot and legrest could be swung underneath the chair to give a completely free foot area.
Q51 (Ease of shortening legrest length)
Frequency counts

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<th>VD</th>
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Q53 (Comfort of shortening legrest length)
Frequency counts

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<th>U</th>
<th>VU</th>
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<td>9</td>
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Q55 (Ease of lengthening legrest length)
Frequency counts

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Q57 (Comfort of lengthening legrest length)
Frequency counts

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<td>4</td>
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</table>

Discussion

The poor response obtained in this section of the questionnaire in relation to the 8L wheelchair was due in the main to two factors. One was the inability of many subjects to use a spanner, whether due to reduced muscle power, painful joints, or lack of mechanical know-how, and the other was the lack of awareness by some subjects that the legrests could in fact be adjusted in length.
c) Footrests (Questions 63 - 74)

<table>
<thead>
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<tr>
<td>Prototype</td>
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</table>

| Q65 (Comfort of removal) |                  |
|            | VC   | C   | S   | U   | VU  | N/A |
| 8L         | 3    | 20   | 4    | 6    | 0   | 3   |
| Prototype  | 14   | 16   | 2    | 1    | 0   | 3   |

| Q67 (Ease of replacement) |                  |
|                          | VE   | E   | S   | D   | VD  | IMP | N/A |
| 8L                       | 3    | 16   | 7    | 5    | 0   | 2   | 3   |
| Prototype                | 14   | 16   | 3    | 0    | 0   | 3   | 0   |

| Q69 (Comfort of replacement) |                  |
|                            | VC   | C   | S   | U   | VU  | N/A |
| 8L                         | 2    | 18   | 6    | 6    | 1   | 3   |
| Prototype                  | 15   | 15   | 2    | 1    | 0   | 3   |
Discussion

There are three methods of removing the footrests on the 8L wheelchair: firstly, by lifting the footplates, secondly by swinging the legrests away, and thirdly by completely removing the foot and legrest units. The few subjects who experienced difficulty in handling the footrests on the 8L wheelchair did so mainly because of the stiffness of the footplate hinge mechanism, or the awkwardness of the legrest swivel location system. Those who found handling the footrests impossible on either chair did so because they could not reach their feet.

With regard to injuries occurring in the pre-test period, approximately half the subjects had experienced some form of physical damage from the footrests. This included trapped fingers, bruised or grazed ankles, and feet trapped behind or between the footplates.

One incident was recorded in association with the prototype chair, involving a bruised heel as a result of the footplate falling. A recurrence of this would be prevented by the inclusion of a friction washer in the footplate hinge mechanism.
d) Brakes (Questions 75 - 86)

<table>
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<tr>
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<th>VD</th>
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<tr>
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<tr>
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<td>27</td>
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</table>
Discussion

The slight difference in responses to the two wheelchairs is explained by the fact that although the brakes were basically similar, the brake handle on the prototype wheelchairs was somewhat longer, giving a greater mechanical advantage to the user with limited strength. However, comment was made by a number of subjects on the type of control handle provided on the prototype wheelchair. This was in the form of a flat disc, and although comfortable to use, was not particularly liked. Preference was expressed for a round knob.

One subject had completely removed the brakes on his 8L wheelchair to facilitate its use for basketball.
8.5.4. Use of wheelchair

a) Transfer (Questions 87 - 102)

Q87 (Ease of transfer to chair)
Frequency counts

<table>
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Q89 (Comfort of transfer to chair)
Frequency counts

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Q95 (Ease of transfer from chair)
Frequency counts

<table>
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<th>VD</th>
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Q97 (Comfort of transfer from chair)
Frequency counts

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<th>VU</th>
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<td>0</td>
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<td>1</td>
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</tbody>
</table>

Discussion

The purpose of these questions was to determine whether any features of the wheelchairs' design hindered or aided transfer, whether the transfer was effected by the user alone, or with the aid of an attendant. The result coded Impossible, therefore,
is an error, as no subject failed to use the wheelchair.

Several causes were mentioned as hindering transfer to and from the 8L wheelchair. Among these were: difficulty in operating armrests, difficulty in operating foot and legrests, height of rear wheel relative to the seat, and buckling up of seat cushion. The single greatest aid to transfer with the 8L wheelchair was the length of the armrests used in standing transfer.

Conversely, the aids to transfer to and from the prototype wheelchair were the operation of armrests and foot and legrests, whereas the difficulty experienced was as a result of the shortness of the armrests.

In terms of attendant-aided transfer, favourable comment was made on the fact that the push handles could be folded away on the prototype wheelchair.

One factor common to both wheelchairs is the difficulty of engaging both brakes when the user is transferring into the wheelchair from the side. It is difficult to see how this problem can be overcome without having a single control mechanism for both brakes.
b) Propulsion (Questions 103 - 112)

Q103 (Ease of propulsion)

<table>
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</tr>
</thead>
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</table>

Q105 (Possibility of propulsion)

<table>
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</table>

Q107 (Comfort of propulsion)

<table>
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<th>U</th>
<th>VU</th>
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Discussion

The deciding factor on ease of propulsion is without doubt the use made of the wheelchair. Many wheelchair users do not attempt to self-propel in situations where self-propulsion might become difficult. This, the great majority of subjects never self-propelled outside the confines of their home.

Where difficulty was experienced with either chair, this was invariably associated with the front castor wheels, either by jamming on uneven ground, or by failing to revolve to the trailing
Impossibility of propulsion was always associated with ground surface: grass, ice, gravel and so on, and not specifically with the design of the wheelchair.

Discomfort in propulsion was associated with two features: the design and position of the handrim, and the design of the backrest. As far as the handrim is concerned, its covering material and proximity to the wheel were criticised on both chairs, and as far as the backrest is concerned, conflicting comment was made. For some individuals, too high a backrest made access to the wheels difficult, whereas for others too low a backrest did not provide the necessary level of backrest reaction to propulsion. A similar conflict of interest appears with the position of the handrim: its closeness to the wheel ensures that the chair is narrow enough to pass through doors, while creating a situation in which injury can occur through trapping the fingers between the handrim and the wheel.
c) Folding (Questions 113 - 120)

**Q113 (Ease of folding)**

<table>
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<th>VD</th>
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**Q114 (Comfort of folding)**

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d) Unfolding (Questions 121 - 128)

**Q121 (Ease of unfolding)**

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**Q123 (Comfort of unfolding)**

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<td>13</td>
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</table>
Discussion

The results reflect the large number of subjects who never attempt to fold or unfold their wheelchairs, and also the similarity of response to the two wheelchairs where folding was attempted, in spite of the differences in mechanisms.
e) Transportation (Questions 129 - 141)

Q130 (Ease of putting chair in car)
Frequency counts

<table>
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<tr>
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<th>S</th>
<th>D</th>
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Q132 (Comfort of putting chair in car)
Frequency counts

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Q134 (Ease of taking chair out of car)
Frequency counts

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Q136 (Comfort of taking chair out of car)
Frequency counts

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<td>0</td>
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</tr>
</tbody>
</table>
Discussion

From the results, it can be seen that:

1. Very few wheelchair users in this sample used a wheelchair in conjunction with a car.

2. The prototype wheelchair could not in its present form be used with an invalid three-wheeler.

3. The size and weight of any wheelchair are critical factors in determining its ease of use with a car. This factor has been taken into account in two ways in considering possible future development of the prototype. Firstly, the solid seat needs to incorporate a folding mechanism when used by individuals needing to take a wheelchair in their car, and secondly, the weight factor needs to be greatly reduced by the use of high density plastics for the frame.
8.5.5. Use of wheelchair with an attendant

a) Propulsion (Questions 142 - 148)

Q142 (Ease of pushing)
Frequency counts

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Q144 (Desirability of handle height adjustment)
Frequency counts

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</table>

Q147 (Comfort of pushing)
Frequency counts

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<th>VU</th>
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</table>

Discussion

The majority of the attendants responding to this section of the questionnaire found that the availability of height adjustment of the push handles offered a greater degree of pushing comfort. However, unfavourable comment was directed by a number of attendants to the shape of the push handles on the prototype wheelchair. Consistent criticism was also made about the castor wheels, on both chairs. These had a tendency to jam on any obstacle, and if not properly aligned with the rear wheels made the chair run to one side.
b) Tipping (Questions 149 - 156)

Q149 (Ease of tipping)
Frequency counts

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Q151 (Comfort of tipping)
Frequency counts

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</table>

Discussion
The one outstanding feature that made tipping the 8L wheelchair difficult was stated to be the shape of the tip bars. These were considered to be the wrong shape for tipping, as either the foot slipped off the tube, or the sharp edges of the tube were painful on the foot. While rubber end stops had been provided initially, these invariably fell off after a period of use.
c) Folding / Unfolding (Questions 157 - 170)

Q157 (Ease of folding)

Frequency counts

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Q159 (Comfort of folding)

Frequency counts

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Q163 (Ease of unfolding)

Frequency counts

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<th>VD</th>
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Q165 (Comfort of folding)

Frequency counts

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Discussion

Folding and unfolding the two wheelchairs presented no real problems to attendants, except when the folding mechanism of the 8L wheelchair had not been lubricated, thus becoming stiff.
d) Transportation (Questions 171 - 181)

Q172 (Ease of putting chair in car)
Frequency counts

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Q174 (Ease of getting chair out of car)
Frequency counts

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Q176 (Comfort of using chair with vehicle)
Frequency counts

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Discussion
As previously discussed, the size and weight of the wheelchair will affect the ease with which it is put into a car. On the 8L wheelchair, comment was specifically directed to the awkwardness of the fixed push handles, and on both chairs the weight was criticised.
8.5.6. General Questions (Questions 183 - 191)

Q183 (Accidents)
No responses are recorded here because of the difference in the time scaling of the comparative evaluation, and the difficulty of persuading subjects to limit their responses to a fixed period of time.

However, the following types of accidents were recorded for the 8L wheelchair, and are given below in order of frequency.
1. Trapped hands going through doors.
2. Feet falling off footrests and suffering damage.
3. User falling out of wheelchair: on one occasion the user fell onto the heel loop retention peg.

The prototype wheelchair was in use for only a short period of time, and no accidents were recorded, but there were two instances of near accidents, both relating to wheelchair stability. In both incidents, the prototype wheelchair threatened to tip forward, suggesting that the resultant centre of gravity of the user and wheelchair should be placed slightly nearer to the rear wheels.

Q185 (Damage to person or property) (8L wheelchair)
The major cause of damage is the wheelchair's footrest, both in terms of damage to property and to the user. The rear wheels were also responsible for some damage, particularly to clothing, as were the backrest material retaining screws.
Q187 (Mechanical failure)

Mechanical failure in the 8L wheelchair occurred mainly in two areas: the footrests and the castors. The footrests frequently become distorted after a period of use, and the castors become distorted and occasionally fall out. This would suggest two things for any design of wheelchair, firstly, that the footrests must be made to withstand the frequent knocks they receive, and secondly, some system of shock absorption should be included to protect the castors.

For the prototype wheelchair, the period of use was not sufficient to produce much evidence of mechanical weakness, but the following was recorded:

1. One subject distorted an armrest by using it as an aid to transfer when it was swung out.
2. On one chair, the leg angle retaining pin sheared.
3. A legrest retaining lug was broken. This was somewhat unusual in that the section of metal broken formed an extension of the main support beam of the wheelchair. However, it is felt only fair to comment that the individual concerned is capable of a degree of wheelchair activity given to few.

Q189 (Appearance of wheelchair)

<table>
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<th>Frequency counts</th>
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Q190 (Overall rating)

Frequency counts

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**Discussion**

These results show that in the main both wheelchairs satisfied the great majority of subjects.
8.6. Conclusion

From an analysis of the results, it will be seen that the 8L wheelchair showed itself to be very acceptable to a large number of the subjects. The two main areas of criticism, which correspond to the two main areas of favourable comment on the prototype wheelchair, were the armrests and foot/legrests. This criticism extended to both the mechanics of the systems, and their handling properties.

By comparing the two wheelchairs, however, it can be seen that the 8L does not offer sufficient easily adjustable features that have been shown to be desirable. For instance, easy leg angle adjustment, legrest length adjustment and push handle adjustment are demonstrably preferable to fixed features, or features which cannot easily be changed.

It is also true that fixed dimensions in terms of seat, back, armrests and footrests cannot ideally suit everyone. Thus, any wheelchair should be designed with the possibility of allowing for the maximum amount of variation for the minimum capital outlay.

It would seem, therefore, that the prototype wheelchair with more inbuilt adjustability and the possibility of providing easily a wide range of feature combinations to the same subframe will be better in terms of human factors and economics.

Finally, comment should be made on the problems attendant on
conducting an evaluation of one's own work. There is a danger that a bias may be introduced quite unwittingly into the results, so comment and discussion on the results have been limited to those features where marked differences were found.

8.7. Mechanical testing

No wheelchair can be considered satisfactory when evaluated solely in terms of human factors. Therefore, methods of calculating the strength and stability of a wheelchair are included as Appendix 5.
CHAPTER 9

9. Special Seating Requirements

9.1. Introduction

Among the normal population and some types of physically disabled, sufficient common anatomical and physiological characteristics exist to provide recommendations for adequate seating support in terms of seat and back length, width, depth and angle etc. Such recommendations, which include the British Standards for seating, assume approximate body symmetry, hip flexion, knee flexion, $5^\circ$ lumbar curve and so forth. With some disabilities, such as certain types of muscular dystrophy, non-functioning or power reduced muscles cause the body to be pulled out of alignment, leading to a variety of body contours, and associated point pressure. (See Figs. 22 and 23) While similarities exist between such individuals in the mechanics of collapse, varieties in degree are very great, and do not always remain static. Furthermore, tender, and sometimes ulcerated prominences of the spine may be present, for instance with spina bifida, and standard seating recommendations will be totally inappropriate for these requirements. These are just two instances where special provision in terms of seating will be needed, and it is with this special, individual seating that this chapter is concerned.

The problem is threefold: firstly there is a need for inexpensive, individually tailored seating to accommodate malformation. Secondly, as so many of these problems are associated with congenital diseases and disabilities, the growth factor must be included. Thirdly, for those who have completed the growth
Fig. 22. Lateral body displacement

Fig. 23. Forward body displacement
period, corrective seating may be needed to minimise the results of malalignment.

9.2. Present solutions

Prior to the research period, two main systems were available for the accommodation of the malaligned within a wheelchair: contoured foam rubber, and laterally adjustable support pads. The techniques of application of these two systems are discussed below.

9.2.1. Contoured foam rubber support

The techniques involved in using foam rubber or plastic as a support system are those of matching the body malformation in its optimum position within the wheelchair with contoured rubber support material. This is achieved by inserting blocks of three-dimensional foam between the occupant and the wheelchair seat and back, and estimating the amount of surplus material to be removed from the blocks to obtain a reasonable fit. The excess material is removed by means of a knife or hot wire, and the quality of the fit is the product of repeated trials and the skill of the operator.

The difficulties of providing adequate support in this way can be listed as follows:

1. Quality of fit is dependent on the individual skill of the operator.

2. It is impossible to accommodate adequately 'hidden' body areas without moving the user into a position that is no longer optimum.
3. Extreme difficulty is experienced in upholstering concaved surfaces with traditional materials and techniques.

4. The quality of fit of the finished system is dependent on the stability of body shape, and it is difficult to accommodate a change in support requirements.

5. It is difficult to place the body in an optimum position and maintain it there without support so that the support system can be fitted.

6. Because of the characteristics of the material, it is difficult to vary and control the level of support in any areas of contact such as the ischial tuberosities.

Time and cost are also factors which affect the availability of the system. Because the quality of fit is dependent on the care taken in matching the material to the body shape, this procedure is often protracted and costly in terms of both man-hours and skills required. To provide a support system of this type, the services of a clinician, technician and upholsterer would be required for varying lengths of time, with no guarantee that the finished article is adequate.

9.2.2. Laterally adjustable support pads

These support pads are commercially available from wheelchair manufacturers, and offer lateral support via their adjustability relative to the wheelchair sides. The advantages of this system of support are its comparative cheapness and flexibility of use. The difficulties involved in this system are those of limitation of movement by the constrained user, and restricted area of use.
9.3. Investigation into an alternative system

Given the limitations of these two systems, it was decided that an alternative system of seating support was necessary, whose provisions would extend beyond those currently available. The general requirements of such a system are that it is:

a) cheap
b) quick
c) easy to apply - to patient and by staff
d) capable of at least partial mass-production
e) capable of integrating with present wheelchairs
f) reliable
g) safe
h) non-toxic
i) hygienic
j) not the cause of ulceration

The specific requirements which will need to be established for each individual are that the system is:

a) the right size and shape
b) posturally corrective
c) effective in terms of support
d) capable of taking existing ulceration into account
e) adaptable for a variety of activities

The only technique discovered capable of fulfilling all these requirements was that of granule displacement.
9.4. Granule displacement technique

The technique of using displaced particles to accommodate body shape has been in existence for a number of years and can be described as follows: small, regular particles such as sand, rice grains or plastic spheres etc. are placed in a flexible container of a size compatible with the body area to be supported, and the body weight used to displace the particles to accommodate surface configuration. In the examination of this technique, publications associated with the application of similar methods in other areas were studied. Prominent among this work was that of the Royal Aircraft Establishment in aircraft seating, and also that of the Egerton Hospital Equipment Ltd. Research Group, which has facilitated the manufacture of an emergency stretcher by that company based on the granule displacement system. Previous work of the present author on granule displacement discussed below under 9.4.1. Phase One was also considered for re-examination, and as no immediate disadvantages were present, it was decided to test the suitability of the method further, as discussed under 9.4.2.

Phase Two.

9.4.1. Phase One

In 1968, a period of research was undertaken to investigate the possibility of applying the technique of granule displacement to the seating requirements of wheelchair users. The research was concentrated in two main areas, firstly to combine the support with a vacuum locking technique to give controlled support, and secondly to select suitable materials.
9.4.1.1. Application of vacuum locking technique

It was shown quite early in the research period that if regularly shaped particles were sealed in an airtight flexible container and a vacuum applied to the container by removing the air, a structure of controlled resilience could be obtained. (See Figs. 24 - 26) It was also shown that by manipulating the encased particles around an object placed on the top surface of the cushion during the evacuation period, the shape produced by the encroachment of this into the cushion could be maintained after its removal. The results of the work showed:
1. a resilient structure could be produced and maintained
2. the structure was capable of accommodating irregular shapes.

9.4.1.2. Selection of materials

The materials used in the above experiments were fragmented polystyrene ceiling tiles enclosed in a rubberised canvas bag. During the filling of the bag it was noticed that friction of the polystyrene particles contained in the partly filled bag produced static electricity. While static electricity was present, the particles were held in suspension in the bag. This feature of the material's properties was considered extremely useful, as back cushioning could be considered which did not require compartmentalisation of a material to offer full support.

A number of container bags were then made up in a PVC material which had similar properties of insulation as the polystyrene particles, and it was found that suspension of the particles could be maintained with the bag in an upright position until
Fig. 24. First test container

Fig. 25. Evacuated container

Fig. 26. Container used as cushion
air evacuation took place. It was also established that poly-
styrene particles were not an ideal material in that they offered
insufficient free-flow characteristics and did not provide a
sufficiently smooth body contact surface. To overcome these
limitations, free formed polystyrene granules were used, and
these were found to have the desired characteristics, and one
further advantage, in that the resilience of the granules could
be varied by controlling the level of granule expansion from the
unexpanded polystyrene bead.

Because of the limited research period at that time, it was not
possible to carry out extensive trials, but a number of the
cushions were offered to wheelchair users for subjective judg-
ment, and the reports were sufficiently encouraging for the unit
where the work was conducted, the Nuffield Orthopaedic Centre,
Oxford, to continue with its development as a system of taking
body casts. (See Figs 27 to 43)

While this technique results in high-quality thermoplastic body
shells which are located in the patient's wheelchair, and offer
personally contoured body support, the limitations of the system
are as follows:
1. difficulty in accommodating for body changes
2. intermediate plaster cast needs to be produced.

9.4.2. Phase Two

The project's research into the use of particle displacement in
body support was divided into two parts. One was to provide
Fig. 27. Subject

Fig. 28. Displacement of spine

Fig. 29. Prepared wheelchair
Fig. 30. Wheelchair C. of G. displacement

Fig. 31. Tilted wheelchair

Fig. 32. Granule filled container
Fig. 33. Preparation of container

Fig. 34. Vacuum pump

Fig. 35. Fitting container into wheelchair
Fig. 36. Partial evacuation

Fig. 37. Locating subject

Fig. 38. Manipulation of container
Fig. 39. Evacuation of container

Fig. 40. Sealed container
Fig. 42. Application of plaster bandage

Fig. 43. Finished plaster cast
for static physical conditions a means of chemically locking the polystyrene granules into any desired shape, and the other was further to explore the potential of vacuum locking the granules to offer a support of variable resistance which could be quickly adapted to satisfy changes in physical requirements.

**9.4.2.1. Chemical locking technique**

The Institute of Polymer Technology, Loughborough University of Technology, was approached to ascertain whether a chemical agent was available for locking polystyrene granules. At that time, no agent was available that had the qualities required, i.e. retention of granule free-flow characteristics prior to locking, and resilience after locking. As a result of the approach, an offer was made of laboratory facilities and technical help by the Institute of Polymer Technology.

**9.4.2.2. Results of chemical lock experiments**

As a result of the investigations carried out using the facilities of the Institute of Polymer Technology, an agent was identified which offered the qualities and characteristics required. The agent identified was a polymer emulsion, trade name Butakon ML 501. The technique used to lock the granules is as follows:

1. Expansion of polystyrene beads
   
The expansion of the polystyrene beads into free-formed granules is achieved by immersing the beads in boiling water for a specified time, the length of which is determined by the size of granule required. An approximate time for a granule diameter of \( \frac{3}{8} \)" is 2 - 3 minutes.
The granules are then dried.

2. Test cushions
The test cushions are made of flexible PVC material to a 16" x 16" x 2" size, and fitted with a filter air evacuation tube and a filler neck. The cushions are three-quarters filled with the granules, and the neck heat sealed.

3. The agent
The polymer emulsion locking agent is introduced into the bag via the air evacuation tube in a quantity sufficient to coat the beads with a thin film. (Approx. measure, 50ml.)

4. Locking procedure
The chemical locking procedure is started by the displacement of the granules within the bag by seated body weight. A vacuum pump is attached to the air evacuation tube of the bag via a liquid trap which prevents any excess emulsion being drawn into the pump. The test cushion, still under vacuum, is then immersed over a one hour period in a bath of hot water (approx. 50°C) to facilitate the separation of the liquid content of the polymer emulsion, and drying and locking together of the granules. (It was discovered that the water immersion method of drying was the only successful one, as the thermal insulation properties of the cushion precluded the use of direct heat.) Finally, the vacuum pump, the
suction of which has been maintained at a constant rate by an integral balance valve, is removed. (See Figs. 44 to 49)

The only disadvantage of the system was found to be in terms of the time needed to dry the emulsion-coated granules. Other systems, e.g. a sodium silicate/CO₂ mixture (Figs. 50 and 51), which theoretically could produce an instant lock, were tried, but with a conspicuous lack of success, so every endeavour was made to convert the successful technique into a system easily operated in workshop rather than laboratory conditions. (See Figs. 52 to 56)

Because the proposed use of the system was in the field of corrective support, which would inevitably be a long-term project, and therefore outside the scope of the present work, the technique was patented (Patent No. 37770/73) and passed over to Loughborough Consultants, Loughborough University of Technology, for exploitation and control.

9.4.2.3. Vacuum locking technique

In order further to investigate the possibilities offered by the vacuum locking technique in terms of individually tailored, easily altered support surfaces, a project was set up jointly with the Welsh National School of Medicine to provide for the support requirements of spina bifida children. This work is discussed in the following chapter.
Fig. 44. Section of Polymer Laboratory

Fig. 45. Expanding beads by boiling
Fig. 46. Evacuated cushion

Fig. 47. Evacuation oven used in direct heat method
Fig. 48. Water immersion method

Fig. 49. Locked cushion supporting weight
Fig. 50. Sodium silicate/CO₂ method

Fig. 51. Metering CO₂ into cushion
Fig. 52. Expansion ratio of polystyrene beads

Fig. 53. Bead boiler

Fig. 54. Granule drier
Fig. 55. Water curing tank

Fig. 56. Immersion of cushion
CHAPTER 10

10. Application and Evaluation of the Body Support System

10.1. Introduction

Having investigated to a satisfactory level the techniques and materials associated with the vacuum lock granule displacement system, the requirement was for the translation of this information into an applicable body support system. This was achieved by the establishment of a joint project with the Welsh National School of Medicine. The advantages offered by this association were substantial, not only in terms of the project's required medical supervision, but also in the selection of subjects to whom the system could be applied, and their clinical monitoring.

10.2. Selection and description of subjects

There were particular problems in respect of seating and seated posture among patients in the Spina Bifida Unit of the Welsh National School of Medicine, and as these problems also included the problem of allowing for growth, it was decided that application of the system should be made under the control of this unit. As there was neither time nor opportunity for extensive controlled testing of the body support system, it was decided to establish its potential usefulness by applying it to a single selected patient whose disability was such that no single wheelchair or other seating system at present available was adequate.

In consultation with the Unit, a patient was chosen for the severity of her seating problem. The patient was a five year old spina bifida girl with a lumbar kyphosis and a compensatory
Fig. 57. Side view, unsupported subject

Fig. 58. Ulcerated kyphosis
Fig. 59. Front view, supported subject

Fig. 60. Side view, supported subject
dorso-lumbar lordosis above the kyphosis. The apex of the kyphosis was ulcerated. The ulcer was mostly clean and dry, but occasionally broke down, and was usually protected by a foam rubber doughnut, held in place by a bandage round the abdomen. This protrusion and ulcer made for an extremely difficult seating problem, and the situation was complicated by other disabilities including double incontinence, partial paralysis of the right arm, inability to support the head, a protruding ribcage which made lying prone uncomfortable, strabismus, and some brain damage resulting in the impossibility of meaningful communication. (See Figs. 57 to 60)

10.3. Initial monitoring

The first requirement was to establish the needs of the child in terms of:

1. clinical requirements
2. day to day handling by the mother in terms of seating
3. child's activities

This was achieved with the co-operation of the clinician and the child's parents.

1. The clinical requirement of any form of seating for the child was primarily that it reduce the size of the ulcer. So that any improvement might be measured at a later date, tracings of the ulcer were made. (See Figs 61 to 63) The secondary requirement was to encourage and maintain an upright posture.
Figs 61 to 63. Actual size of ulcer
2. Day to day handling in terms of seating was established by the application of a monitoring questionnaire by the child's parents for a period of one week. The format of the questionnaire (see Appendix 6) was deliberately simple, and aimed only at providing information relating to the activities of the child, and the supporting surfaces used. The reason for this was that without knowledge of the existing situation, it would not be possible to establish many of the criteria for a new design, and there was therefore an overriding requirement for the situation to be known in a form uncontaminated by the presence either of an observer or of a questionnaire which might of itself cause changes to occur.

As the child attended a special school each morning, the monitoring took place in the afternoons and early evenings for a total of five days (total time 27 hours 5 minutes). Because the child's level of activity and communication was so low, it was not possible to establish any connection between type of seating, comfort and activity, and because the convenience of the mother also played a large part in the choice of seating, there could be no correlation made between the moods of the child and the types of seating chosen.

However, the following pattern emerged: four main seating surfaces were used: an easy chair and a settee, with the child propped up with pillows; the Yorkhill chair; the Baby Buggy. The easy chair (23% of total time) and the settee (26% of total time) were used mainly for play activity and watching the television. The Yorkhill chair (32% of total time) was used almost exclusively for mealtimes.
The Baby Buggy (17% of total time) was used for mobility, so that the child could be with her mother more conveniently. A very short time (20 minutes) was also spent with the child on the floor. On average, the child was moved five times each half-day.

3. The child's activities at this stage were found to be so limited that the choice of seating was not activity-related.

10.4. Criteria for support design

The general criteria are listed under 9.3. above. The specific requirements are:

1. Right size and shape

To ensure the optimum size and shape of the support, the following measurement were taken of the child:

1. Sacrum to popliteal (including spinal protuberance) 30.5 cm
2. Foot to popliteal 24.0 cm
3. Buttocks width 26.8 cm
4. Scye width 25.4 cm
5. Shoulder width 33.0 cm
6. Sitting height 71.2 cm
7. Shoulder height (seated) 53.0 cm
8. Elbow to seat 12.7 cm

Because of the difficulty in supporting the child in an upright posture, some of these measurements can only be approximate. It is also realised that they are not all true anthropometric measurements as they are not necessarily taken from bony prominences, but it was considered that they would serve quite adequately
in guiding the choice of outer support, as the inner support must by its very nature provide a closer fit.

As a result of these measurements, support shells for the seat and back were chosen of the following dimensions:

- **Seat:**
  - width: 32.5 cm
  - depth: 30.5 cm

- **Backrest:**
  - width: 32.5 cm tapering to 28.5 cm at top
  - height: 30.5 cm

In view of the approximate nature of the anthropometric measurements, adjustability of parts was provided as far as possible. This affected the headrest, footrest and back angle, and the options were left open for altering fixed parts such as the seat, back and armrests.

2. **Posturally corrective**

No postural correction was needed.

3. **Effective in terms of support**

A headrest support was necessary, as was support for the trunk, at an angle greater than 90° from the horizontal. As the optimum angle of support was not known, an adjustable backrest was necessary.

4. **Capable of taking existing ulceration into account**

Because of the position of the ulcer, and the lack of sensation present, it was decided that the best way of taking the ulceration
into account was by providing a backrest which left the area affected totally free of pressure.

5. Adaptable for a variety of activities

The support needed to be used for: long term sitting comfort; play activities; mealtimes, thus including a tray; mobility, if not independent, then at least by the mother. It was not known whether the child was capable of self-propulsion but it would be an obvious advantage if this could be achieved. It was also considered desirable that the support could be placed on the floor, thus allowing for an extension of play activity, including more participation in play with siblings.

10.5 Design and construction of support

In the interests of cost, reproducibility and time, it was decided to use as far as possible readily available component parts for the support. Thus, a Model 8C wheelchair was obtained for its frame and wheel pattern. The canvas seat and back were removed so that the support could be introduced. The basis of the seat/back support was a children's school chair in polypropalene, manufactured by Hille International Ltd. This chair was the second of five sizes made to BS 3040. It was chosen because of the cut-out in the backrest which corresponded exactly to the position of the protuberance and ulcer on the child's spine, and because of its suitable dimensions. This chair had a fixed seat/back angle of 90°, and as the condition of the child necessitated an adjustable angle, modifications were made in the form of back separation from the seat. Linkage of the seat and back was made by means of metal pivots attached to each side of the chair. These pivots allowed the chair back to be moved through an
angle of 90° relative to the seat from the original 90° position. This movement was controlled by a friction mechanism attached to the underside of the seat, and operated on a rod fixed to the rear of the backrest.

The connection of the support to the modified 8C wheelchair was made by the location of two C-section metal clamps positioned to embrace the metal tubes which previously supported the canvas seat. The connection was maintained by the child's body weight acting on the wheelchair's cross-frame which supported both the wheelchair's side members and the seat tubes. When removed from the wheelchair, the C-section clamps, which were approximately 30 cm in length, formed, by their attachment to the support, the base for placing the support on the floor.

The custom-built components of the support system included the headrest and the upholstery.

To satisfy the head support requirements of the child, a laterally concaved headrest was included in the support's design. The headrest was fabricated in such a way as to offer compound adjustment to the head, as well as height adjustment relative to the back. The headrest support face was upholstered with a 2.5 cm layer of polyurethane foam covered with sheepskin.

The upholstery of the support consisted of two parts: the granule-filled PVC bag, and tailored sheepskin covers. Because of the relatively small support area considered, the seat and back
granule cushion was made up by one bag. (See Figs. 64 and 65)
The shape of the bag was determined by the profile of the poly-
propalene chair and the back configuration of the child. The
cushion was secured to the polypropalene chair by PVC and metal
ties.

The support offered by the cushion was made through the displace-
ment of free formed polystyrene granules of approximately 3 mm
diameter. Displacement of the granule-filled cushion by user
weight and hand manipulation ensured a close correlation between
the cushion and the supported body surface. This close correla-
tion was maintained during the support's use by the evacuation
of air from the support cushion. This was achieved by the
application of a hand-operated vacuum pump to the filtered bleed
tube integral with the support cushion. Having obtained the
required level of cushion resilience determined by the level of
evacuation, the bleed tube was secured so that air was excluded
from the cushion, and the pump removed. The shape of the cushion
could be altered by the reintroduction of air into the cushion
and the remanipulation of the granules.

The sheepskin covers were made to fit as closely as possible the
profile of the unevacuated support cushion. Their attachment to
the support was achieved by a continuous wire insert that located
behind the polypropalene chair. This method of attachment enabled
the sheepskin to be removed for laundering. The sheepskin used
was of the trimmed shearling variety of 2.5 cm fibre length and
22µ-28µ fibre diameter, which allows free circulation of air.
Fig. 64. Granule filled cushion in support position

Fig. 65. Extended cushion
The technique developed for making the pattern for the cushion involved the scaling up to life size of profile photographs of the body area to be supported. This made possible the creation of paper patterns on which the PVC support cushion could be modelled. It was thought that in future applications, it would be possible to use a grid on the photographs and scale the grid points up to life size.

10.6. Testing of the support system

When the chair and support system had been completed, consideration was given to the way in which it could be appraised in use. Three areas were considered: the clinical aspect, day to day handling, and the child's activities.

1. Clinical aspect

As previously stated, the main clinical requirement was for a reduction in the size of the ulcer, and to measure any change, tracings of the ulcer were made. Other aspects were also considered, for instance possible reduction in any dependent oedema of the legs, but no oedema was present. Bowel and bladder evacuation patterns could not be used as indices of change, as the bowel was manually evacuated, and there was continuous overflow incontinence of urine. It was also not possible in the circumstances to use measurements of heart rate or oxygen uptake, as long term results were considered more important than short term, and the intellectual state of the child made the application of such monitoring systems inappropriate.

As it was envisaged that modifications may be needed to the
first prototype, it was decided not to request clinical evaluation until a level of acceptability to the mother had been achieved.

2. Day to day handling
At first, it was considered that the most appropriate method of evaluating the chair and support in terms of day to day handling by the mother would be by a questionnaire. However, it was soon realised that this could realistically cover only aspects of the mechanical properties of the system in terms of ease, comfort and safety of use, and would offer very little information about changes in day to day handling routine. Also, it was not known what sort of improvements or problems might occur, so even open-ended questions might be too restrictive. It was decided finally to produce as comprehensive a list as possible of points for comment as an aide-memoire, and to ask the parents to write on these or any other aspects of the system and its use as they wished.

3. Child's activities
Apart from any information arising from the parents on the child's activities, the teacher at the child's school was also approached and asked to comment on any change or improvement in activity following the application of the system, and as a result of it. (See Appendix 7 for post-application monitoring formats)

10.7. Fitting of the support
With the fabrication of the support system and modification of the Model 8C wheelchair, arrangements were made for the unit to
be fitted under medical supervision to the selected patient. The fitting of the support and wheelchair unit took place at Cardiff Royal Infirmary, with the object of ascertaining the following:

1. that the medical staff of the Spina Bifida Unit considered the system safe for initial application
2. the system's provisions in terms of size and range of adjustment were adequate
3. the support and associated wheelchair could be operated by the patient's attendants
4. the system's design was acceptable to the individuals concerned.

10.7.1. Preparation of the patient

Before placing the child in the support system, which for this section of the trial had been located in the wheelchair, street clothing and the foam pressure pad which protected the ulcer were removed. This was done to enable an observation to be made of the closeness of fit to be achieved between the patient and the supporting system.

10.7.2. State of ulcer

With the removal of the pressure pads, a visual check was made on the state of the ulcer, and it was judged to be in a stable and passive condition with no sign of breakdown.

10.7.3. Preparation of the support

The support, having been mounted in the wheelchair, was prepared
by removing the lap tray from its location at the front of the chair. Air was then allowed to permeate throughout the support cushion by withdrawing the stop from the filter tube. The polystyrene granules contained in the support cushion were then manipulated to ensure an even distribution, and the small hand vacuum pump connected to the filter tube.

10.7.4. Location of the patient in the support

With the support's backrest in a slightly reclined position from vertical, the patient was placed in the support, and adjustments made to the headrest and backrest angles of presentation to ensure the required posture. The polystyrene granules were remanipulated to produce the closeness of fit required, and the air was then drawn from the cushion using the small hand pump to the required level of cushion resilience. When this was achieved, the pump nozzle was removed from the cushion filter tube, and the tube stop replaced.

With the adjustment of the support and the locking off of the cushion, the lap tray was replaced, and the following observations made:

1. an extremely close fit could be achieved between the patient and support
2. all the adjustments to the support and chair could be made by the attendants
3. the support's size equated well with the proportions of the patient
4. with the tray and wheelchair armrests fitted, the
patient was secure in the support

4. the headrest provided adequate support for the head without restraining voluntary movement.

10.7.5. Recommendations

Two factors which involved slight modifications to the support and chair came to light as a result of the support's occupation while in the wheelchair. These were:

1. raising of the footrests above the maximum allowed by the design of the 8C wheelchair. This was required as a direct result of lifting the seat height of the wheelchair slightly above the range of adjustment of the footrests.

2. an increase in the locking capacity of the support's headrest. This was due to an unforeseen factor that related to pressure exceeding that of normal head loading being applied. It was observed that after the patient had been in the support for some time, a repeated and voluntary extension of the body took place, resulting in substantial pressure being applied to the headrest. This was thought to be due to the requirement of the patient for sensory feedback from the remaining body areas that possessed feeling and function.

10.7.6. Floor location of the support

Having tested the provisions of the support within the wheelchair, the patient was removed and the support was placed on the floor.

When positioned this way, the support was used in association with
Fig. 66. Support unit assembly

Fig. 67. Modified 8C wheelchair
Fig. 68. Support and wheelchair

Fig. 69. Subject in wheelchair
Fig. 70. Floor use

Fig. 71. C-clamp base

Fig. 72. Subject in support
the lap tray, but without armrests. These had not been included as part of the support's design, as the whole function of the support when used on the floor was to facilitate a greater use of the hands and arms of the user. It was observed that while the support offered a certain amount of lateral stability, a lap belt was required to ensure complete safety. The fitting of a lap belt would, it was thought, offer the required stability without frustrating the extended use of hand and arm mobility provided by the support's proximity to the floor.

10.8. Conclusions
After approximately two hours' occupation of the support, the patient was observed to be relaxed and happy, and an examination of the ulcer's condition when the patient was removed from the support showed no visible change in the ulcer.

In view of the satisfactory comments made by the medical staff and the patient's attendants, arrangements were made for the modifications to be carried out locally. A photographic record was taken (see Figs. 66 to 72) and the chair and support were handed over for continued use and subsequent patient monitoring.

10.9. Final monitoring developments
After several days' use of the support system and associated wheelchair, and before the alterations were carried out, the monitoring programme and use of the support system were stopped. This was due to a slight breakdown in the condition of the ulcer brought about by pronounced and forceful movements of the subject.
when seated in the support. These movements, which took the form of strong, backward motion of the head, were first noted as a factor to be accommodated for during the initial fitting of the system. At that time it was felt that an upgrading of the headrest friction mechanism would satisfy the support demands of this movement by providing a strong reaction to it. However, the effect of providing firm resistance to the subject's head resulted in a forward displacement of the body in the support.

The consequences of this were twofold. Firstly the subject lost the desired upright posture, and secondly, shear stress was applied to the ulcer as a product of body/support mismatch.

Accepting the premise that the first requirement of any piece of equipment is to maintain the physical well-being of its user, the support and wheelchair were removed for analysis and modification.

10.9.1. Modifications to support system and wheelchair

After a careful analysis of the provisions of the support system and wheelchair in association with the recorded observations of the subject's parents, it was decided that the modifications to the support and wheelchair should be based on the following:
1. Control of the body movement, but without tight restriction.
2. Ensuring that the body returned after movement to its supported optimum posture.

The accommodation of these requirements was made by including the following in the design of the support system and wheelchair:
1. Headrest fixed in the optimum position
2. Backrest fixed in the optimum position
3. Seat rake angle increased to 10° downwards from seat front to back
4. Increased subject penetration into seat and back cushion by providing a less densely packed cushion
5. Arm supports of the lap tray extended to control lateral stability of the subject more accurately
6. Slide and lock facility given to the lap tray to enable a closer fit to be maintained between subject and tray
7. Range of footrest adjustment increased beyond the range offered by the wheelchair to allow more positive reaction to the feet
8. Upholstery changed from treated sheepskin to natural fabric to increase the control offered by the evacuated cushion. Although sheepskin is theoretically the ideal upholstery material, it was discovered that when used to cover a small surface area, its bulk negates most of its desirable qualities.

After modification of the support and wheelchair (see Figs 73 to 80), these were returned to the subject and the monitoring programme continued.

10.10 Results
After a period of three weeks' use of the support and wheelchair, the following comments were received from the child's mother. Where criticisms are made, recommendations for adjustment and modification are given.
Fig. 73. Modified system

Fig. 74. Rigid shell, headrest and cushion
Fig. 75. Tray in support position

Fig. 76. Tray in extended position
Fig. 77. Back view of chair and system.

Fig. 78. Support and folded wheelchair.
Fig. 79. Model showing propelling position

Fig. 80. Stand-in model
a) Mechanics of system

1. Upholstery

"The upholstery is of a serviceable material and colour".

2. Cushion

"The cushion does not mould to Lisa's shape as intended, she has to wear pads to protect the ulcer at all times (night and day). These, together with her clothes, prevent any adequate contact being made between Lisa and the cushion, because of the bulk involved".

Recommendation

Ideally, the system of malleable cushions should accommodate for the sacral protuberance and padding. In the attempt to draw a balance between unrestrictive support and ulcer protection, the system erred on the side of being unrestrictive. It therefore needs enlarging to accommodate for the padding and to offer more lateral support.

3. Headrest

"The headrest is improved since being made more rigid".

4. Backrest adjustment

This does not apply to the modified system.

5. Support to wheelchair fitting

"Support to wheelchair fitting very cumbersome to handle in day to day use, so this part of the system has been
Recommendation

It is difficult to see how this fitting can be simplified while a standard model wheelchair is used. Further discussion of this aspect of the system is made under 10.11.2.

6. Tray

"Tray is more adequate since being enlarged".

7. Armrests ) "No comment to add here, as wheelchair
             )
8. Footrests ) is no asset to support, as previously
             )
9. Brakes ) mentioned".

Recommendation

Further research is needed to ascertain the fundamental reasons for the dislike of the Model 8C wheelchair as a base.

10. Overall size, shape, weight

"Size and shape do not present any undue problems.
Weight can be a bit much if it is attempted to move Lisa while she is sitting in the chair".

Recommendation

For indoor use, as an alternative to the wheelchair, a base on castor wheels may be useful as a wheelbase. (See section b.4. Use on floor)
11. Safety

"More can be done here to increase the safety by adding some form of straps, otherwise the system cannot be used unless the tray is permanently in position".

Recommendation

A lap strap should be included.

12. Convenience

No comment made

13. Cleaning

b) Operation of system

1. Pushing

"Not applicable"

2. Feeding

"Feeding is not successful in the support on its own as it means that Lisa has to stay at floor level which makes her inclined to play with her food rather than eat it. If the support is fitted to the wheelchair so that she can be brought more to table level, this then means the support is at an angle tilting backwards, so that anything on the tray will obviously slide towards her, making feeding difficult. This also applies to any other type of activity which is attempted while the support is fitted to the wheelchair base".
Recommendation

A tray should be provided whose angle of presentation is adjustable so as to remain parallel with the floor for those activities where this is necessary. There is a difference of requirement between support and activity which must be considered.

3. Transfer into and out of chair

"Transfer into and out of the chair is not a problem in itself, only a bit inconvenient from the point of view of having to fit the catches on the tray. It means my having to get down on hands and knees to be able to check that the catches are screwing in properly, and are secured".

4. Use on floor

"From Lisa's point of view, it means she can watch television from this level, and sit with her sister, but the tray has to be kept in position to make sure she does not fall out. Also, great care has to be taken by other members of the family that Lisa's legs are not stepped on as they pass her. (There is a measure of protection afforded her legs when the tray is in position.) But I have attempted to leave Lisa without the tray. This then makes her legs lie on the floor which could prove to be dangerous.....She is also inclined to try and pull herself out of the system by holding on to the front underside of the chair. This means she rocks forward onto her face where she then
has to stay as she is unable to get herself back into the chair. This could perhaps be eliminated with the aid of straps. When she does get into this position, the system stays on the floor and does not fall on top of her which is a good thing. This would suggest to me that the system is at least stable on the floor. Lisa is still inclined to go to one side or the other when she is tired, and so she hangs her head over the side).

Recommendations

As above: lap strap, wheeled base and larger cushion.

5. Alterations in day to day routine

"There isn't any noticeable alteration in her routine, only that with the tray being larger she is able to have more in front of her. This then enables her to have finger paints or crayons to hand as well as paper".

6. Limitations of use

"All activities are carried out in the system while it is on the floor as this means the tray is reasonably straight".

7. Appearance

"Has not really been of concern at the present time".

8. Use with car

"Use with car not attempted. I feel it is not suitable from this point of view as it cannot be secured, and
she would not be able to use safety straps".

c) Child's activities

1. Self propulsion

"Although I have as stated disregarded the wheelchair frame because of its bulk and being cumbersome to use with the support, when I have had the support attached to the wheelchair, Lisa did attempt to propel herself, not very successfully because it was rather heavy for her to move, but nevertheless if when the mobility of the system is to be developed she has at least shown that the interest to move is there".

Recommendation

Lighter, possibly smaller, wheelchair.

2. Increase in range of activity  )
    ) No comment made

3. Limitation in range of activity }

10.11. Discussion

10.11.1. The support

Although the support has not achieved a level of complete acceptability, an analysis of the comments made during its test period shows that with the following additions and alterations a high level of correlation would be possible between the requirements and the provisions.

1. The cushion

The shape of the cushion need altering so that a
higher degree of lateral support is offered. This could be achieved by increasing the wall size of the cushion to give the effect of lateral concavity to the seat and back surfaces. The depth of this concavity would need to be established in relation to the level of activity possible by the child. If too much lateral support is provided, a frustration of arm and trunk movement would result.

2. The tray

While the tray offers a high degree of body retention, it is obvious that it does not fully satisfy all the demands made on it. The tray's angle of presentation needs to be adjustable to suit the type of activity involved.

3. Lap strap

At present, the only body retention facility is that provided by the tray. It is considered desirable to provide an alternative system, probably in the form of a retention strap which could be located to span the armrests. This could be made of a material whose level of resilience could be varied to offer only as much support as is required.

4. Wheeled base

The flexibility and stability of the system is such that it could easily be placed on a small, wheeled base. There are many possibilities of design which could be
tried, including those based on a transit chair configuration with four castor-wheeled legs, a Chailey Heritage trolley type base which allows self-propulsion, and various others.

10.11.2. The wheelchair

As far as the use of the support with a wheelchair is concerned, this proved less than ideal. While every effort was made to produce a simple and easy connection between the support and the wheelchair, and to relate the remaining provisions to the wheelchair to the requirements of the child, the solution produced was not acceptable. In terms of the child's use of the wheelchair, self-propulsion was attempted, but the weight of the wheelchair was too great. For other activities, alterations as described above would be needed to the tray. In terms of the mother's involvement, the difficulties experienced need more careful examination. It seems most unlikely, however, that a satisfactory solution will be produced by using a standard model wheelchair as a base, and consideration will therefore have to be given to an alternative, specially designed method of providing mobility outdoors. Consideration will also be needed of a method to convert the support for use as a feeder/high chair. This could be done either in conjunction with outdoor mobility, or as an extension of the wheeled base already discussed, or as a separate static base.
10.12. School monitoring

After a three week period of use at school, comment on the system's level of acceptability was sought. Comments made fell into two areas: that of the support, including the cushion and the tray, and the other specifically the wheelchair on which the support was mounted.

10.12.1. The support

It was found that the modifications made to the original support had done much to improve its level of acceptability. Favourable comment was made on the tray both as a restraining device and as a work surface. It was found that with the addition of a non-slip mat to the tray, feeding was now possible from the wheelchair. Satisfaction was expressed with the other provisions of the support, particularly when used in association with the floor.

Criticism of the support was directed specifically at the size of the cushion. This was felt to be on the small side, and did not offer the level of support required.

10.12.2. The wheelchair

With regard to the wheelchair, it was found that the greatest limiting factor in terms of the child's use of the wheelchair was the position of the push handles' supporting bars which frustrated self-propulsion.
It is unfortunate that a greater period of time was not available to carry the project through to a level of complete acceptability. However, the progress made within the six month period of the project was sufficiently encouraging to suggest that an extension of the work is desirable. This is shown by the fact that extensive use is made of the support, in spite of the limitations already commented on. After two months, the support was in daily use in the home, and used in preference to any other seating surface.

It has been shown that it is possible to provide cheap adaptive seating on an individual basis, but the findings so far need to be substantiated in the following way:

1. Implementation of the recommendations made.
2. Clinical assessment.
3. Trials with a larger sample population.
CONCLUSION

This thesis, and the work associated with it, has attempted to show in detail the role of the ergonomist in the design and evaluation of an assistive device for the disabled. The main difference in his role in this instance from his role with the able population is in the impossibility of defining a single function for any feature. For instance, armrests do support the arms, but they also act as body stabilisers, as an aid to transfer, as a base for a tray and so on, and it is not possible either to satisfy all the requirements with a single recommendation, or to have a consistent list of priorities for all users. It is thus the role of the ergonomist to make as comprehensive a list of different uses of features as possible, and to evaluate the level of acceptability of the designs offered.
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APPENDIX 1

WHEELCHAIR QUESTIONNAIRE
SUBJECT

1. Name

2. Age

3. Sex

4. Handedness

5. Total length of time in a wheelchair

6. Length of time in present wheelchair

7. Type of accommodation: bungalow, terraced house, semi-detached, detached, institution

8. Ownership of motor vehicle and type

9. Presence of attendant: never occasionally often always

10. Cause of disability
Please answer the following questions about sitting in the wheelchair; bearing in mind your experiences over the past week.

a) **SEAT**

Is the seat:

1. Width: too wide  too narrow  just right
2. Depth: too deep  too shallow  just right
3. Height: too high  too low  just right
4. Angle: too sloping  too flat  just right
5. Surface: too hard  too soft  just right
6. How comfortable is the seat to sit on:
   VC: C S U VU
7. If U or VU, a) where is the discomfort felt and b) what causes it
   a) 
   b) 

b) **Backrest**

Is the Backrest:

8. Height: too high  too low  just right
9. Width: too wide  too narrow  just right
10. Contour: too rounded  too flat  just right
11. Angle: too sloping  too upright  just right
12. Surface: too hard  too soft  just right
13. How comfortable is the backrest to lean on:
    VC: C S U VU
14. If U or VU, a) where is the discomfort felt and b) what causes it
    a) 
    b)
ARMRESTS

Are the armrests:

15. Height: too high too low just right
16. Length: too long too short just right
17. Width: too wide too narrow just right
18. Distance apart: too far apart too close together just right
19. Surface: too soft too hard just right

20. How comfortable are the armrests to lean on:

VC C S U VU

21. If U or VU, a) where is the discomfort felt and b) what causes it
   a)
   b)

FOOTRESTS

Are the footrests:

22. Length: too long too short just right
23. Width: too wide too narrow just right
24. Angle: too sloping too flat just right
25. Height: too high too low just right
26. Control: Do the footrests hold your feet:
   too much not enough just right

27. How comfortable are the footrests in use:

VC C S U VU

28. If U or VU, a) where is the discomfort felt and b) what causes it
   a)
   b)
29. How easy is it to remove the armrests:

VE E S D VD IMP

30. If D, VD or IMP, say why the difficulty is experienced, in terms of the design of the armrest eg:

a) position of the locking mechanism
b) design of the locking mechanism
c) design of the armrest
d) any other reason

(Please specify as fully as possible)

31. How comfortable is it to remove the armrests:

VC C S U VU

32. If U or VU, a) where is the discomfort felt and b) what causes it

a) 

b)

33. How easy is it to replace the armrests:

VE E S D VD IMP

34. If D, VD or IMP, say why the difficulty is experienced in terms of the design of the armrest

(Please specify as fully as possible)
35. How comfortable is it to replace the armrests:
   VC  C  S  U  VU

36. If U or VU, a) where is the discomfort felt and b) what causes it
   a)

   b)

37. Did you at any time hurt yourself while using or operating the armrests: YES/NO

38. If YES, please specify

39. Are there any particular advantages or disadvantages in terms of your normal activities in the design of the armrests
   a) advantages  b) disadvantages

40. Any further comments about the armrests.
How easy is it to raise the angle of the legrest:
VE  E  S  D  VD  IMP

(N/A: Go to Q51)

If D, VD or IMP, say why the difficulty is experienced in terms of the design of the legrest eg:

a) position of adjustment mechanism
b) design of adjustment mechanism
c) design of legrest
d) any other reason

(Please specify as fully as possible)

How comfortable is it to raise the angle of the legrest:
VC  C  S  U  VU

If U or VU, a) where is the discomfort felt and b) what causes it.

a) 

b) 

How easy is it to lower the angle of the legrest:
VE  E  S  D  VD  IMP

If D, VD or IMP, say why the difficulty is experienced in terms of the design of the legrest

(Please specify as fully as possible)
CHRISTIE WHEELCHAIR ONLY.

47. How comfortable is it to lower the angle of the legrest:
   VC  C  S  U  VU

48. If U or VU, a) where is the discomfort felt, and b) what causes it
    a)
    b)

49. Did you hurt yourself while raising or lowering the legrest:
    YES/NO

50. If YES, please specify

51. How easy is it to shorten the legrest length:
    VE  E  S  D  VD  IMP  N/A

52. If D, VD or IMP, say why the difficulty is experienced in terms of the design of the legrest. eg:
    a) position of locking mechanism
    b) design of locking mechanism
    c) design of legrest
    d) any other reason

    (Please specify as fully as possible)
53. How comfortable is it to shorten the legrest length:
   VC C S U VU

54. If U or VU, a) where is the discomfort felt and b) what causes it
   a)
   b)

55. How easy is it to lengthen the legrest:
   VE E S D VD IMP N/A

56. If D, VD or IMP, say why the difficulty is experienced in terms of the design of the legrest
   (Please specify as fully as possible)

57. How comfortable is it to lengthen the legrest:
   VC C S U VU

58. If U or VU, a) where is the discomfort felt and b) what causes it
   a)
   b)

59. Did you at any time hurt yourself while using or operating the legrests: YES/NO

60. If yes, please specify

61. Are there any particular advantages or disadvantages in terms of your normal activities in the design of the legrest
   a) advantages          b) disadvantages
62. Any further comments about the legrests

FOOTRESTS (Q 63 and 67: observe operation)

63. How easy is it to remove the footrests:

VE E S D VD IMP

64. If D, VD or IMP, say why the difficulty is experienced in terms of the design of the footrest eg:

a) position of locking mechanism
b) design of locking mechanism
c) position of swing mechanism
d) any other reason

(Please specify as fully as possible)

65. How comfortable is it to remove the footrests:

VC C S U VU

66. If U or VU, a) where is the discomfort felt and b) what causes it

a)

b)

67. How easy is it to replace the footrests:

VE E S D VD IMP

68. If D, VD or IMP, say why the difficulty is experienced in terms of the design of the footrests

(Please specify as fully as possible)
69. How comfortable is it to replace the footrests:
   VC  C  S  U  VU

70. If U or VU, a) where is the discomfort felt and b) what causes it
    a)
    b)

71. Did you at any time hurt yourself while using or operating the
    footrests: YES/NO

72. If YES please specify

73. Are there any particular advantages or disadvantages in terms of
    your normal activities in the design of the footrests
    a) advantages  b) disadvantages

74. Any further comments about the footrests

75. BRAKES (Q75 and 79: observe operation)
   How easy is it to put the brakes on:
   VE  E  S  D  VD  IMP

76. If D, VD or IMP, say why the difficulty is experienced in terms
    of the design of the brakes eg:
    a) the position of the brake lever
    b) the design of the brake lever
    c) the design of the brake mechanism
    d) any other reason

    (Please specify as fully as possible)
77. How comfortable is it to put the brakes on:
   VC C S U VU

78. If U or VU, a) where is the discomfort felt and b) what causes it
    a)  
    b)  

79. How easy is it to put the brakes off:
   VE E S D VD IMP

80. If D, VD or IMP, say why the difficulty is experienced in
    terms of the design of the brakes
    (Please specify as fully as possible)

81. How comfortable is it to put the brakes off:
   VC C S U VU

82. If U or VU, a) where is the discomfort felt and b) what causes it
    a)  
    b)  

83. Did you at any time hurt yourself while using or operating the
    brakes.
    YES/NO
84. If YES, please specify

85. Are there any particular advantages or disadvantages in terms of your normal activities in the design of the brakes
   
   a) advantages       b) disadvantages

86. Any further comments about the design of the brakes.
PART IIIa: USE OF WHEELCHAIR

TRANSFER

87. Using your most convenient method of transfer, how easy has it been to get into the wheelchair:

VE E S D VD IMP

88. If D, VD or IMP, say why the difficulty was experienced eg:

a) design of the wheelchair or parts of wheelchair
b) design of surface you transfer from
c) any other reason

(Please specify as fully as possible)

89. How comfortable has it been to get into the wheelchair:

VC C S U VU

90. If U or VU, a) where was the discomfort felt and b) what caused it

a) 

b) 

91. Did you at any time hurt yourself while getting into the wheelchair

YES/NO

92. If YES, please specify
93. Are there any particular advantages or disadvantages in the design of the wheelchair in terms of getting into it  
a) advantages b) disadvantages

94. Any further comments about getting into the wheelchair

95. Using your most convenient method of transfer, how easy has it been to get out of the wheelchair:  
VE E S D VD IMP

96. If D, VD or IMP, say why the difficulty was experienced  
(Please specify as fully as possible)

97. How comfortable has it been to get out of the wheelchair:  
VC C S U VU

98. If U or VU, a) where was the discomfort felt and b) what caused it  
a)  
b)

99. Did you at any time hurt yourself while getting out of the wheelchair:  
YES/NO

100. If YES, please specify
101. Are there any particular advantages or disadvantages in the design of the wheelchair in terms of getting out of it
   a) advantages    b) disadvantages

102. Any further comments about getting out of the wheelchair

PROPULSION

103. Did any feature of the wheelchair's design ever make it difficult for you to propel yourself: YES/NO

104. If YES, in association with what design feature, and in what circumstances was the difficulty experienced eg:

   DESIGN FEATURE                CIRCUMSTANCE
   a) position of propelling wheels a) type of ground surface
   b) size of propelling wheels    b) confined spaces
   c) type of handrim              c) any other reason
   d) type of castor              
   e) any other reason

(Please specify as fully as possible)

105. Did any feature of the wheelchair's design ever make it impossible for you to propel yourself: YES/NO.

106. If YES, in association with what design feature, and in what circumstances was this impossible

107. How comfortable has it been to propel yourself in the wheelchair:

   VC   C   S   U   VU
108. If U or VU, where was the discomfort felt and what caused it
   a)
   b)

109. Did you hurt yourself while propelling the wheelchair: YES/NO

110. If YES, please specify

111. Are there any particular advantages or disadvantages in terms of self-propulsion in the design of the wheelchair
   a) advantages  b) disadvantages

112. Any further comments about propelling yourself in the wheelchair

   c)

FOLDING

113. How easy has it been for you to fold the wheelchair:
   VE   E   S   D   VD   IMP
   (N/A, go to Q 129)

114. If D, VD or IMP, say why the difficulty was experienced in terms of the wheelchair design eg:
   a) the design of the seat locking mechanism
   b) the position of the seat locking mechanism
   c) removal of the seat
   d) the design of the folding mechanism
   e) any other reason
115. How comfortable has it been to fold the wheelchair: VC C S U VU

116. If U or VU, a) where was the discomfort felt and b) what caused it
   a) 
   b) 

117. Did you hurt yourself while folding the wheelchair: YES/NO

118. If YES, please specify

119. Are there any particular advantages or disadvantages in terms of folding the wheelchair in the wheelchair's design
   a) advantages  b) disadvantages

120. Any further comments about folding the wheelchair

121. How easy has it been for you to unfold the wheelchair: VE E S D VD IMP
122. If D, VD or IMP, say why the difficulty was experienced in terms of the wheelchair's design eg:

a) unfolding mechanism  
b) replacement of seat  
c) seat locking mechanism  
d) any other reason

(Please specify as fully as possible)

123. How comfortable has it been to unfold the wheelchair:

VC C S U VU

124. If U or VU, a) where was the discomfort felt and b) what caused it

a)  
b) 

125. Did you hurt yourself while unfolding the wheelchair: YES/NO

126. If YES, please specify

127. Are there any particular advantages or disadvantages in terms of unfolding the wheelchair in the wheelchair's design

a) advantages  
b) disadvantages

128. Any further comments about unfolding the wheelchair
129. What type of motor vehicle do you drive. (If none, answer NONE, go to Q.183)

130. How easy has it been to put the wheelchair into the vehicle:
   VE  E  S  D  VD  IMP

131. If D, VD or IMP, say why the difficulty was experienced in terms of the wheelchair's design eg:
   a) size of wheelchair
   b) weight of wheelchair
   c) any other reason
   
   (Please specify as fully as possible)

132. How comfortable has it been to put the wheelchair into the vehicle:
   VC  C  S  U  VU

133. If U or VU, a) where was the discomfort felt and b) what caused it
   a) 
   b) 

134. How easy has it been to get the wheelchair out of the vehicle:
   VE  E  S  D  VD  IMP

135. If D, VD or IMP, say why the difficulty was experienced in terms of the wheelchair's design
   
   (Please specify as fully as possible)
136. How comfortable has it been to get the wheelchair out of the vehicle:

VC C S U VU

137. If U or VU, a) where was the discomfort felt and b) what caused it

a)

b)

138. Did you hurt yourself while getting the wheelchair into or out of the vehicle: YES/NO

139. If YES, please specify

140. Are there any particular advantages or disadvantages in the wheelchair's design when used with a motor vehicle

141. Any further comments about using the wheelchair with a motor vehicle
PART 111b: USE OF WHEELCHAIR WITH AN ATTENDANT

TO BE ANSWERED BY THE ATTENDANT (if none, go to Q.183)

PROPULSION

142. Did any feature of the wheelchair's design ever make it difficult to push the wheelchair: YES/NO

143. If YES, in association with what design feature and in what circumstances was the difficulty experienced eg:

<table>
<thead>
<tr>
<th>DESIGN FEATURE</th>
<th>CIRCUMSTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) position of handles</td>
<td>a) type of ground surface</td>
</tr>
<tr>
<td>b) design of handles</td>
<td>b) confined spaces</td>
</tr>
<tr>
<td>c) type of wheels</td>
<td>c) any other reason</td>
</tr>
<tr>
<td>d) any other reason</td>
<td></td>
</tr>
</tbody>
</table>

(Please specify as fully as possible)

144. Do you consider height adjustment of the handles desirable: YES/NO

145. Give reasons for your answer to Q.144

CHRISTIE WHEELCHAIR ONLY

146. Give your comments on the method of handle height adjustment where this is available

147. How comfortable was it to push the wheelchair:

VC C S U VU
148. If U or VU, a) where was the discomfort felt and b) what caused it
a)  

b)  

TIPPING  

149. Did any feature of the wheelchair's design ever make it difficult
to tip the wheelchair: YES/NO  

150. If YES, in association with what design feature and in what
circumstances was the difficulty experienced eg:

<table>
<thead>
<tr>
<th>DESIGN FEATURE</th>
<th>CIRCUMSTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) position of handles</td>
<td>a) type of ground surface</td>
</tr>
<tr>
<td>b) design of handles</td>
<td>b) weight of wheelchair user</td>
</tr>
<tr>
<td>c) position of tip bars</td>
<td>c) any other reason</td>
</tr>
<tr>
<td>d) design of tip bars</td>
<td></td>
</tr>
<tr>
<td>e) any other reason</td>
<td></td>
</tr>
</tbody>
</table>

(Please specify as fully as possible)

151. How comfortable was it to tip the wheelchair:
VC C S U VU  

152. If U or VU, a) where was the discomfort felt and b) what caused it
a)  

b)  

153. Did you hurt yourself while pushing or tipping the wheelchair
YES/NO
154. If YES, please specify

155. Are there any particular advantages or disadvantages in terms of pushing or tipping in the design of the wheelchair
   a) advantages       b) disadvantages

156. Any further comments about pushing or tipping the wheelchair

FOLDING/UNFOLDING

157. How easy was it to fold the wheelchair:
    VE  E  S  D  VD  IMP

158. If D, VD or IMP, say why the difficulty was experienced in terms of the wheelchair's design eg:

   a) design of seat locking mechanism
   b) position of seat locking mechanism
   c) removal of seat
   d) design of folding mechanism
   e) any other reason

(Please specify as fully as possible)

159. How comfortable was it to fold the wheelchair:
    VC  C  S  U  VU
160. If U or VU, a) where was the discomfort felt and b) what caused it
   a)
   
b)

161. Did you hurt yourself while folding the wheelchair: YES/NO

162. If YES, please specify

163. How easy was it to unfold the wheelchair:

   VE  E  S  D  VD  IMP

164. If D, VD or IMP, say why the difficulty was experienced in terms of the wheelchair's design
     (Please specify as fully as possible)

165. How comfortable was it to unfold the wheelchair:

   VC  C  S  U  VU

166. If U or VU, a) where was the discomfort felt and b) what caused it
   a)
   
b)

167. Did you hurt yourself while unfolding the wheelchair: YES/NO

168. If YES, please specify
169. Are there any particular advantages or disadvantages in terms of folding or unfolding the wheelchair in the wheelchair's design
   a) advantages  b) disadvantages

170. Any further comments about folding or unfolding the wheelchair

TRANSPORTATION

171. What type of motor vehicle do you put the wheelchair into. If none, answer NONE

172. How easy was it to put the wheelchair into the vehicle:
   VE  E  S  D  VD  IMP

173. If D, VD or IMP, say why the difficulty was experienced eg:
   a) size of wheelchair
   b) weight of wheelchair
   c) size of vehicle interior
   d) size of vehicle boot
   e) any other reason

   (Please specify as fully as possible)

174. How easy was it to get the wheelchair out of the vehicle:
   VE  E  S  D  VD  IMP

175. If D, VD or IMP, say why the difficulty was experienced

   (Please specify as fully as possible)

176. How comfortable was it to get the wheelchair into and out of the vehicle:
   VC  C  S  U  VU
177. If U or VU, a) where was the discomfort felt and b) what caused it.
   a)
   b)

178. Did you hurt yourself while getting the wheelchair into or out of the vehicle: YES/NO

179. If YES, please specify

180. Are there any particular advantages or disadvantages in the wheelchair's design when used with a motor vehicle
   a) advantages   b) disadvantages

181. Any further comments about using the wheelchair with a motor vehicle

GENERAL COMMENTS BY ATTENDANT

182. Please give any further comments you may have on the design of the wheelchair or any of its parts.
PART IV: GENERAL QUESTIONS

183. Did you have any accidents or near accidents directly related to the wheelchair: YES/NO

184. If YES, please specify

185. Has the wheelchair ever caused any damage to you or your property: YES/NO

186. If YES, please specify

187. Did the wheelchair ever fail to perform satisfactorily: YES/NO

188. If YES, please specify

189. How would you rate the appearance of the wheelchair:
    Very pleasing, Pleasing Satisfactory Displeasing Very displeasing

190. How would you rate the chair overall:
    Very good Good Fair Bad Very bad

191. Any further general comments.
192. Are there any additional questions regarding the wheelchair or its use which you feel should have been included in this questionnaire? If so, please give them below, together with your response.
APPENDIX 2

WHEELCHAIR QUESTIONNAIRE TOPICS
WHEELCHAIR QUESTIONNAIRE: TOPICS

1. SITTING IN THE WHEELCHAIR
   a) Seat
   b) Backrest
   c) Armrests
   d) Footrests

2. HANDLING OF PARTS OF THE WHEELCHAIR
   a) Armrests
   b) Legrests
   c) Footrests
   d) Brakes

3a. USE OF WHEELCHAIR
   a) Transfer
   b) Propulsion
   c) Folding
   d) Unfolding
   e) Use with vehicle

3b. USE OF WHEELCHAIR WITH AN ATTENDANT
   a) Propulsion
   b) Tipping
   c) Folding/unfolding
   d) Use with vehicle

4. GENERAL QUESTIONS
   a) Safety
   b) Reliability
   c) Appearance
APPENDIX 3

USE OF OWN WHEELCHAIR
USE OF OWN WHEELCHAIR

1. Did you at any time revert to your own wheelchair: YES/NO

2. If YES, please complete the following for each time you used your own wheelchair

   a) Amount of time spent in own wheelchair:
      1st 2nd 3rd 4th 5th 6th occasion occasion occasion occasion occasion occasion

   b) Reason for use of own wheelchair:
      1st occasion
      2nd occasion
      3rd occasion
      4th occasion
      5th occasion
      6th occasion

Please continue overleaf if necessary
APPENDIX 4

WHEELCHAIR QUESTIONNAIRE : ANALYSIS OF RESULTS

SEE INSIDE BACK COVER
APPENDIX 5

WHEELCHAIR STABILITY ANALYSIS AND MECHANICAL TEST
Introduction

This Appendix offers equations for the calculation of wheelchair stability and loading. It is divided into three parts: Part A covers the stability of and forces applied to a stationary wheelchair, Part B covers the stability and forces applied to a dynamic wheelchair. With regard to safety, the wheelchair occupant is at risk in two main areas: wheelchair instability, and wheelchair mechanical failure. Wheelchair stability is a product of wheelbase and resultant centre of gravity displacement, and the equations offer the possibility of determining maximum displacement of resultant centre of gravity in relation to the wheelbase of any particular chair.

In terms of forces applied to a wheelchair, the equations represent the maximum loading occurring with a 95th percentile weight male user capable of equalling the fastest self-propelled wheelchair velocity as recorded in the Paralympic Games. The loadings are calculated on the assumption that the stability of the wheelchair is maintained, and cannot include abnormal situations. Thus, for a wheelchair passing freely over a kerb, the kerb height cannot be such that the resultant centre of gravity of the user plus chair lies outside the horizontal presentation of the wheelbase.

Part C gives worked examples of the major equations, using for illustration data taken from the current DHSS model 8L wheelchair. Where distinct similarities exist between equations, substitution of data has been restricted to one equation.
In the final section of Part C examples are given of test situations which would satisfy the calculated maximum loading that the wheelchair parts would be subjected to. The number of repetitions of wheelchair test loading can only be decided in relation to the maximum level of wheelchair activity, and this must of necessity be an arbitrary decision.

It should be noted that for an application of the equations to other wheelchairs it will be necessary to obtain particular data from those wheelchairs.
WHEELCHAIR STABILITY ANALYSIS

A. Static wheelchair
   A.1. Longitudinal stability
   A.2. Lateral stability
   A.3. Wheelchair standing on a slope
   A.4. Wheelchair mounting a kerb
   A.4.1. Forces applied to the front axles
   A.4.2. Forces applied to the handles
   A.5. Forces applied to the armrests

B. Dynamic wheelchair
   B.1. Longitudinal stability
   B.2. Wheelchair going round a banked curve
   B.2.1. Inward banking
   B.3. Wheelchair passing over a kerb

C. Worked examples
A. STATIC WHEELCHAIR

A.1. Longitudinal stability

Condition: wheelchair stationary on an inclined surface with rear wheels braked. Wheelchair facing up slope.

Problem: at what angle of slope will the wheelchair slide or tip backwards?

\[ FIG. A-1 \]

- \( O \) - centre of gravity of system
- \( \theta \) - inclination of surface
- \( c \) - distance between castor wheel and centre of gravity (can be varied)
- \( a \) - wheelbase
- \( W \) - total weight of chair and user. If needed each can be treated separately
Maximum value of $\Theta$ is needed so that the chair is just sliding. Brakes are applied at the rear wheels only. The main equations involved are:

\[ \sum F_x = 0, \quad \sum F_y = 0, \quad \sum N_o = 0 \text{ for the equilibrium.} \]

Final results are:

\[ N_2 = \frac{W \sin \Theta}{\mu} \quad \text{--- (1)} \]

\[ N_1 = W \cos \Theta \left[ 1 - \frac{\tan \Theta}{\mu} \right] \quad \text{--- (2)} \]

where $\mu$ is the coefficient of friction between the surface and the rubber tyres of the wheelchair.

For tipping: when the wheelchair tips backwards, the point of contact at the front wheels is removed. Therefore $N_1$ becomes 0. Therefore $\tan \Theta = \mu \quad \text{--- (3)}$

Equation (3) is the condition for tipping.

Given that the value of $\mu$ can be calculated for a surface, then the maximum angle of inclination that can maintain wheelchair stability is slightly less than the value of $\Theta$ for backwards tipping, and for sliding the equation is:

\[ \tan \Theta = \frac{\mu c}{a - h \mu} \quad \text{--- (4)} \]

N.B. $\Theta$ is maximum angle of slope on which the wheelchair will not slide.

For a given chair, $a$, $c$ and $h$ are known. We have selected $\mu$. Hence $\Theta$ can be calculated from equation (4). This is the maximum value of the slope which the chair can stand. Therefore the ramp or slope should be designed for $\Theta$ given by equation (4).
A.2. Lateral stability

Condition: wheelchair stationary across an inclined surface at right angles to slope.

Problem: at what angle of slope will the wheelchair and user tip?

The final equations are:

\[ \tan \phi = \mu \quad (5) \]
\[ N_4 = \frac{W \cos \phi}{b} \left( d + \mu h \right) \quad (6) \]
\[ N_3 = W \cos \phi \left[ 1 - \frac{d + \mu h}{b} \right] \]  \hspace{1cm} (7)

For tipping, \( N_3 = 0 \)

Therefore \( d = b - \mu h \)  \hspace{1cm} (8)

For a given wheelchair, \( d, b \) and \( h \) are fixed. Let us say we have selected \( \mu \). (Rubber and pavement, \( \mu \approx 0.7 \) to 0.9, giving \( \phi = 35^\circ \) for a value of \( \mu = 0.7 \))

If equation (8) is satisfied, then there will be sideways tipping.
A.3. Wheelchair standing on a slope

Condition: wheelchair facing down slope, with rear wheels braked.
Problem: at what angle of slope will the wheelchair slide?

The final equations are:

\[ N_5 = \frac{W \sin \theta}{\mu} \quad \text{(9)} \]
\[ N_6 = W \cos \theta \left[ 1 - \frac{\tan \theta}{\mu} \right] \quad \text{(10)} \]
\[ \tan \theta = \frac{\mu c}{a + \mu h} \quad \text{(11)} \]

Since the front wheels are not braked, the chair slides before any tipping. If the front wheels are braked, the problem is similar to the sideways stability problem, with b and d rewritten in terms of a and c.

Therefore the maximum slope the chair can stand in this position is given by equation (11).
A.4. Wheelchair mounting a kerb.

A.4.1. Forces applied to the front axles

Condition: chair mounting a kerb.

Problem: what force needs to be applied to the front axles to enable the wheelchair to mount a kerb whose height is less than the radius of the castor wheels?

\[ \begin{align*}
W_1 & \quad \text{weight taken by the front wheel} \\
W & \quad \text{force applied to the front axle} \\
h_1 & \quad \text{kerb height} \\
a_1 & \quad \text{radius of the front wheel}
\end{align*} \]
Analysis shows:

\[
P = \frac{W_1 (2a_1 h_t - h_t^2)^{\frac{1}{2}}}{a_1 - h_t}
\]  \hspace{1cm} (12)

For a given wheelchair, \( a_1 \) and \( W_1 \) are known, and if \( h_t \) is given then \( P \) can be calculated. If the calculated value of \( P \) becomes greater than that which can be applied by the user, then the user will be unable to mount the kerb.
A.4.2. Forces applied to the handles

Point c acts as a pivot

d - point of application of the force P
d moves in an arc as does the centre of mass o. Let the angle
turned through be \( \theta \) radians. N.B. \( \pi \) radians = 180°.

Distance moved by the point of application of the force =
\[ = cd \sin (\alpha + \theta) \, d\theta \]

Corresponding distance moved by the centre of mass =
\[ = co \cos (\phi + \theta) \, d\theta \]

From the principle of Virtual Work done,
\[ P \left[ cd \sin (\alpha + \theta) \, d\theta \right] = W \left[ co \cos (\phi + \theta) \, d\theta \right] \]
Simplifying,

\[ P = W \left[ \frac{\cos \phi}{\cos \varphi} \right] \frac{\cos \phi \left( a^2 - h_1^2 \right)^{\frac{1}{2}} - h_1 \sin \phi}{\sin \varphi \left( a^2 - h_1^2 \right)^{\frac{1}{2}} + h_1 \cos \varphi} \]  

\[ (13) \]

\( P \) is the force applied to the handles to mount a kerb of height \( h_1 \).
A.5. Forces applied to the armrests

Condition: forces on wheelchair armrests due to suspended body weight.

\[ \tan \theta = \frac{x}{a}, \quad \sin \theta = \frac{x}{(x^2 + a^2)^{1/2}}, \quad \cos \theta = \frac{a}{(x^2 + a^2)^{1/2}} \]

\( W_1 \) and \( W_2 \) are the weights of the subject's arms. \( W_3 \) is the weight of the subject's body without the arms.

\[ \sum H_A = -A_y d + W_2 (d - c) + W_3 (d - b) + W_1 (d - a) = 0 \]

\[ \sum H_C = 0 = A_H - C_H \]
Therefore,

\[ A_H = C_H \]  \hspace{1cm} (14)

Knowing a, b, c and d and \( W_1, W_2 \) and \( W_3 \), we can find \( A_V \) and \( C_V \).

\[ \tan \theta = \frac{A_V}{A_H} \]

Therefore, \( A_H = \frac{A_V}{\tan \theta} \) \hspace{1cm} (15)

\[ \sin \theta = \frac{A_V}{A_R} \]

Therefore, \( A_R = \frac{A_V}{\sin \theta} \) \hspace{1cm} (16)

\( A_R \) is the resultant force acting on the armrests.
B. DYNAMIC WHEELCHAIR

B.1. Longitudinal stability (See Fig. B-1)

Condition: user propelled wheelchair ascending a slope.

Problem: what angle of slope in association with what propulsion force will produce tipping?

\[ W = m_w g + m_r g \] (Also, \( W = mg \))

Rear wheel only

\[ m_w g = \text{weight of rear wheel, where } m_w = \text{mass of wheel.} \]

The rest of the chair

\[ m_r g = \text{weight of chair without rear wheels.} \]

Let \( L \) be the torque of known magnitude exerted on the driving wheel (rear wheel) shaft, either by user or a motor.

\( H = \text{internal force component in the x direction} \).

\( V = \text{internal force component in the y direction} \).

Equations of motion used are:

- Force in x direction = \( m \ddot{x} \) (\( \ddot{x} \) is the acceleration in the x direction)
- Force in y direction = \( m \dot{y} \)

Moment about \( Q = I \ddot{\theta} \), where \( I = \text{moment of inertia} \), \( \ddot{\theta} = \text{angular acceleration} \).
FIG. B-1

Rear wheel only

The rest of the chair
The final results are:

\[ F = mg \left( \sin \theta + \frac{\ddot{x}}{g} \right) \]  

(17)

where \( mg = W \) = weight of the entire system

\[ = (m_w + m_r)g \]

\( \ddot{x} \) = acceleration up the gradient

\( g \) = acceleration due to gravity.

\[ \ddot{x} = \frac{g \left[ \frac{L}{mgr} - \sin \theta \right]}{1 + \left[ \frac{m_w}{m_r} \frac{k}{r} \right]^2} \]

(18)

where \( k \) is the radius of gyration of the rear wheels.

\[ H = m_r g \left[ \sin \theta + \frac{\ddot{x}}{g} \right] \]

(19)

\[ N_1 = m_r g \left[ \frac{a - c}{a} \right] \cos \theta - \frac{1}{a} \left[ L + H (h - r) \right] \]

(20)

\[ N_2 = mg \cos \theta - N_1 \]

(21)

\[ V = N_2 - m_w g \cos \theta \]

(22)

The necessary coefficient of friction \( \mu = \frac{F}{N_2} \).

It may be seen from equation (18) that if the torque provided by the user is too small, \( \ddot{x} \) will be negative and the chair will not be able to ascend the gradient. On the other hand, if \( L \) is too large \( N_1 \) will be negative. Actually the chair will tip over backwards as soon as \( L \) is large enough to reduce \( N_1 \) to zero.
B.2. Wheelchair going round a banked curve

B.2.1. Inward banking

Condition: wheelchair travelling at a constant speed around a banked curve of radius $R$

Problem: what is the velocity of the wheelchair when tipping occurs?

*FIG. B-2-1*
\[ \sum F_x = 0 \]

Therefore, \(-(N_3 + N_4) \sin \theta - (F_3 + F_4) \cos \theta = \frac{-mV^2}{R} \).

\[ \sum F_y = 0 \]

Therefore, \((N_3 + N_4) \cos \theta - (F_3 + F_4) \sin \theta = mg \).

If \((F_3 + F_4) = \mu (N_3 + N_4),\)

\[ \frac{V_s^2}{V_s} = Rg \left[ \frac{\sin \theta + \mu \cos \theta}{\cos \theta - \mu \sin \theta} \right] \]

or \[ \frac{V_s^2}{V_s} = Rg \left[ \frac{\mu + \tan \theta}{1 - \mu \tan \theta} \right] \]

where \(V_s\) is the velocity at which slipping occurs.

Taking moments about the mass centre,

\[-N_4 (b - d) - (F_3 + F_4) h + N_3 d = 0 \]

Also \(N_3 + N_4 = \frac{mg}{\cos \theta - \mu \sin \theta}\)

Therefore, expressions for \(N_3\) and \(N_4\) can be written.

To examine tipping \(N_4 = 0\)

Equations are:

\[ N_3 \sin \theta + F_3 \cos \theta = \frac{mV^2}{R} \]

\[ N_3 \cos \theta - F_3 \sin \theta - mg = 0 \]

\[ N_3 d - F_3 h = 0 \]
Therefore

\[ \frac{F_3}{N_3} = \frac{d}{h} \]

Therefore tipping cannot occur before slipping unless exceeds \( \frac{d}{h} \).

Further, speed at tipping:

\[ v_T^2 = Rg \left[ \frac{\sin \theta + \left( \frac{d}{h} \right) \cos \theta}{\cos \theta - \left( \frac{d}{h} \right) \sin \theta} \right] \quad (2\frac{1}{4}) \]

N.B. For outward banking of the curve, (\( \theta \)) in equations (23) and (2\( \frac{1}{4} \)) should be replaced by (-\( \theta \)).
B.3. Wheelchair passing over a kerb

Condition: wheelchair passing over a kerb.
Problem: what is the loading on the castor wheels?

Let $u$ (m/sec) be the velocity of the chair and $h$ (metres) be the height of the kerb and $x$ (metres) be the distance measured horizontally from the kerb where the wheels first make contact.

Let $u$ = horizontal velocity, $v$ = vertical velocity.
Let $v_r$ be the resultant striking velocity.
$\theta$° is the striking angle.
Final results

Duration of flight: \( t = 0.451(h)^{\frac{1}{2}} \) secs. \( \text{(25)} \)

Horizontal distance: \( x = 0.451u(h)^{\frac{1}{2}} \) metres. \( \text{(26)} \)

Striking velocity: \( v_r = (u^2 + 19.62h)^{\frac{1}{2}} \) m/sec. \( \text{(27)} \)

Striking angle: \( \alpha^0 = 90 - \tan^{-1}\left(\frac{u}{4.43(h)^{\frac{1}{2}}}\right) \). \( \text{(28)} \)

Linear impulse = \( \frac{W}{g} v_r \) \( \text{(29)} \)
c. WORKED EXAMPLES
ALL DISTANCES ARE MEASURED IN CENTI METRES.

\[ cd = 66.0 \quad zg2 = 46.5 \]
\[ cg_1 = 28.5 \quad zg3 = 45 \]
\[ de = 22.0 \quad tf = 15.0 \]

\( o_1 \) is the centre of gravity of the chair alone
\( o_2 \) is the centre of gravity of the user
\( o \) is the resultant centre of gravity of chair plus user
\( w_1 \) is the weight of the chair
\( w_2 \) is the weight of the user
\( W \) is the resultant weight of chair plus user
\( g_1 \) is the origin of the orthogonal axes
NOTE All calculations included in examples are based on data taken from DHSS wheelchair Model 8L. For other wheelchairs, substitution of data from particular wheelchair should be used.

EXAMPLE

Location of the resultant centre of gravity of wheelchair plus user

\[ w_1 = (17.5g) \text{ Newtons} \quad w_2 = (97.5g) N \quad W = w_1 + w_2 \]
\[ x_1 = 17.0 \text{ cms} \quad x_2 = 25.0 \text{ cms} \quad \text{m} = (115.0g) N \]
\[ h_1 = 35.3 \text{ cms} \quad h_2 = 72.8 \text{ cms} \quad = (115.0 \times 9.81) N \]
\[ = 1130 N \]

N.B. \( w_1, x_1, h_1 \) from wheelchair

\( w_2 \) established from 95th percentile civilian male population,

(ref. U.S. National Health Survey, 1960

\( x_2, h_2 \) from Swearingen (1962)

From the moment method

\[ x = \frac{w_1x_1 + w_2x_2}{W} = 23.8 \text{ cms} \]
\[ h = \frac{w_1h_1 + w_2h_2}{W} = 67.0 \text{ cms} \]
A.1. Longitudinal Stability

Backward movement, down slope, (braked).

\[ a = g_1g_3 + g_2g_3 = 51.0 + 4.5 = 55.5 \text{ cms} \]
\[ c = (a - x) = 55.5 - 23.8 = 31.7 \text{ cms} \]

For static stability, the point o must fall within the wheelbase. Maximum slope sustained without tip, is when o lies directly above \( g_1 \).

Therefore, maximum slope = \[ \tan \theta = \frac{x}{h} = \frac{23.8}{67.0} = 0.355 \]

Therefore, \( \theta = 19.5^\circ \)

From equation (4),

\[ \tan \theta = \frac{\mu c}{a - h\mu} \]

where \( \mu = 0.35 \) for rubber on smooth pavement.

Therefore,

\[ \tan \theta = \frac{0.35 \times 31.7}{55.5 - 67 \times 0.35} = 0.346 \]

Therefore \( \theta = 19.1^\circ \)
A.3. Wheelchair standing on a slope (braked)

Equation (11), \( \tan \theta = \frac{\mu_c}{a + \mu h} \)

By substitution, \( \tan \theta = 0.1014 \)

Therefore, \( \theta = 6.5^\circ \)
A.4.1. Horizontal force applied to front axle in mounting a kerb

Moments about \( g_1 \) give,

\[ W_1 \times 46.5 = W \times 23.8 \]

Therefore,

\[ W_1 = \frac{(115.0 \times 9.81) \times 23.8}{46.5} = 576.0 \text{ N} \]

From equation (12)

\[ P = \frac{576 \left(2 \times 9.525 \times 6 - 6 \times 6\right)}{9.525 - 6} \]

, where kerb height

\[ h_1 = 6.0 \text{ cms} \]

\[ = 1445 \text{ N} \]
A.4.2. Forces applied to the handles in tipping the chair

From equation (13), when \( h_1 = 0 \),

\[
P = \frac{W \cos \phi}{\cos \delta / \sin \alpha}
\]

\[= P_{\text{max}} = \text{Maximum static loading on handles}
\]

Therefore, \( P_{\text{max}} = (115.0 \times 9.81) \left( \frac{45.25}{66.0} \right) \left( \frac{\cos 58.3}{\sin 16} \right) \)

\[= 1470 \text{ N}
\]

Introduction of tip bars gives the following:

Taking moment about \( g_1 \),

\[P(d_e - 3.8) + T(t_f) = Wx
\]

Substituting the values

\[P(22.0 - 3.8) + T(15.0) = 1130(23.8)
\]

When \( P = \text{maximum} \), \( T = 0 \) and

when \( T = \text{maximum} \), \( P = 0 \).

Maximum pull applied to handles in overcoming kerb height.

\[P_1 = \text{Horizontal pull}
\]

Taking moment about \( g_1 \),

\[P_1(92.0) = 1130(23.8)
\]

Therefore \( P_1 = 292.0 \text{ N} \)
B.1. Longitudinal stability

Forces required to propel independent wheelchair up a slope of 1 in 12.

Let torque applied about the rear axle be 30 Nm in this case.

Therefore $L = 30$ Newton metres

$m_wg = 4.55 \times 9.81 = 44.5 \text{ N}$

$m_r g = 1092 \text{ N}$

$a = 46.5 \text{ cms}, c = 46.5 \text{ cms} - 23.8 = 22.7 \text{ cms}, h = 67 \text{ cms},

r = 28.5 \text{ cms}, \tan \theta = \frac{1}{12} = 0.0834, \quad \theta = 4.8^\circ$

Let $k = 0.9r = 0.9 \times 28.5 = 25.6 \text{ cms}$.

From equation (18),

$$\ddot{x} = \frac{9.81 \left[ \frac{30 \times 100}{1130 \times 28.5} - 0.0837 \right]}{1 + \frac{44.5}{1130} \left( \frac{25.6}{28.5} \right)^2}$$

$$= 0.0912 \text{ metre/sec}^2$$

From equation (17)

$$F = 1130 \left( 0.837 + \frac{0.0912}{9.81} \right)$$

$$= 105.0 \text{ N}$$
From equation (19)

\[ H = 1092 \left( 0.0837 + \frac{0.0912}{9.81} \right) \]

\[ = 101.5 \text{ N} \]

From equation (20)

\[ N_1 = 1092 \left[ \frac{46.5 - 22.7}{46.5} \right] 0.9965 - \frac{1}{46.5} \left[ 30 \times 100 + 101.5(67 - 28.5) \right] \]

\[ = 408.5 \text{ N} \]

From equation (21)

\[ N_2 = 1130 \times 0.9965 - 408.5 \]

\[ = 716.5 \text{ N} \]

The necessary coefficient of friction \( \mu = \frac{F}{N_2} \)

\[ = \frac{105}{716.5} \]

\[ = 0.147 \]
B.3. Wheelchair passing over a kerb

For a wheelchair to maintain stability, the resultant centre of gravity \( o \) must lie within the wheelbase. Therefore given

\[
\begin{align*}
\frac{h_1}{h} \leq \frac{ac}{(h^2 + c^2)^{\frac{1}{2}}} \\
\text{maximum kerb height equals } h_1 = \frac{46.5 \times 22.7}{(67^2 + 22.7^2)^{\frac{1}{2}}} = 15 \text{ cms}
\end{align*}
\] 

Maximum self-propelled velocity = 4.98 metres/sec. (Paralympic Games, 1971, 100 metres dash)

Therefore, from equation (27), striking velocity

\[
v_r = (u^2 + 19.62h_1^{\frac{1}{2}}),
\]

where \( u^2 = (4.98)^2 = 24.75 \)

\( h_1 = 0.15 \text{ m} \)

\( v_r = 5.26 \text{ metres/sec} \)

Energy of impact taken by castor wheels =

= kinetic energy at impact

\[
= \frac{1}{2} \frac{m}{g} v_r^2 = \frac{1}{2} \times \frac{1130}{9.81} \times 5.26^2 \text{ Newton metres}
\]

\[= 160 \text{ Nm} \]
This is the energy absorbed by castor wheels at impact, and can be translated for test purposes into a variable weight travelling through a variable height.

Illustration of test situation

Given a fixed mass of 100 kgs \((m_t)\), the height required \((H_t)\) to simulate the energy absorbed at impact is given by,

\[
m_t g H_t = \frac{1}{2} \frac{W}{g} v_r^2
\]

\[
100 \times 9.81 \times H_t = 160
\]

Therefore \(H_t = \frac{160}{100 \times 9.81} = 0.1635 \text{ metre}\)

Impact energy taken by the rear wheel passing over a kerb of height 15 cms:

Proportion of wheelchair and user weight acting over the rear wheels = \(W_2 = 554 \text{ N}\), from moments taken about the point \(g_2\).

Therefore energy at impact = \(554 \times 0.15 = 83 \text{ Nm}\)

Given a fixed mass of 100 kgs \((m_t)\) the height \((H_t)\) required to simulate the energy absorbed at impact is given by,

\[
m_t g H_t = 83
\]

Therefore,

\[
H_t = \frac{83}{100 \times 9.81} = 0.0847 \text{ metre}
\]
Energy absorbed by the footrest in supporting a proportion of user body weight in passing over a kerb of height 15 cms.

Given that each footrest carries 6.0 per cent of total body weight, load carried by each footrest =

\[= 97.5 \times \frac{6}{100} = 5.85 \text{ kgs.}\]

Therefore, energy at impact = K.E. = \(\frac{1}{2} \times 5.85 \times v^2\)

\[= 81 \text{ Nm}\]

Given a fixed mass of 10 kgs \(m_t\) the height \(H_t\) required to simulate the energy absorbed at impact is given by,

\[m_t g H_t = 81\]

Therefore \[H_t = \frac{81}{10 \times 9.81} = 0.826 \text{ metre}\]

For each armrest, given static loading 5.0 per cent of body weight, i.e. 4.87 kgs,

Energy at impact = K.E. = \(\frac{1}{2} \times 4.87 \times v^2\)

\[= 67.5 \text{ Nm}\]

Therefore test height required given a fixed mass of 10 kgs =

\[= \frac{67.5}{10 \times 9.81} = 0.684 \text{ metre}\]
Energy absorbed by the seat in supporting a proportion of user body weight in passing over a kerb of height 15 cms.
Given that the percentage of body weight equals 78 per cent of the total, load carried by the seat is

\[ = 97.5 \times \frac{78}{100} = 76 \text{ kgs} \]

Therefore energy at impact = K.E.

\[ = \frac{1}{2} \times 76 \times v_r^2 \]

\[ = 1055 \text{ Nm} \]

Given a fixed mass of 100 kgs \((m_t)\), the height \((H_t)\) required to simulate the energy at impact is given by,

\[ m_t g H_t = 1055 \]

Therefore \( H_t = \frac{1055}{100 \times 9.81} = 1.075 \text{ metres} \)
APPENDIX 6

BODYSUPPORT SYSTEM: INITIAL MONITORING
INITIAL MONITORING

Monitoring Record Card

Day...........

1. Type of chair
2. Why selected
3. Activity
4. Initial posture
5. Change in posture
6. Initial mood
7. Change in mood
8. Time spent in chair
9. Comments

Visual state of ulcer

Day........

Better )
) in what way
Worse )
Same
Notes on Monitoring

1. Type of chair. Please fill in name of chair (Yorkhill etc) or type of chair (easy chair etc) or any other supporting surface used (bed, floor), and use a different card each time the child is placed in a chair during one day.

2. Why selected. For instance: usual chair for feeding, going out etc. or child restless, needed change of sitting surface because of discomfort.

3. Activity. For instance: feeding, washing, etc. or playing (with what), radio, TV, going out etc.

4. Initial posture. When the child was first put in chair, what posture was adopted? Head supported/not supported, back upright/slumped etc.

5. Change in posture. While the child was in the chair, did the posture change? (e.g. slump, fall sideways, pull upright etc) Who made the change, the child or yourself?

6. Initial mood. For instance: happy, restless, glad of change of chair/activity etc.

7. Change in mood. As the child remains in the chair, does the mood change from that initially observed?

8. Time spent in chair. For each period the child spent in this particular chair, please record time.

9. Comments. This space is available for any further observations made about the child in this particular chair, e.g. attempts at moving the chair, particular difficulties or advantages etc.

At the beginning and end of each day, please also complete the section on the visual state of the ulcer, whether it is the same, or whether it is better or worse, and in what way.
APPENDIX 7

BODY SUPPORT SYSTEM : POST - APPLICATION MONITORING
Notes on the application of the body support system

The spina bifida wheelchair is made up of two main parts: firstly the wheelchair frame, including wheels, armrests, brakes etc., and secondly the body support system including support shell with subframe attached, headrest, cushion and sheepskin upholstery. The connection between the body support system and the wheelchair is made by clipping the metal runners beneath the support shell over the parallel bars located one on each side of the wheelchair at seat height.

Instructions
1. To remove the support from the wheelchair, lift sharply
2. To replace the support in the wheelchair, press down. It may help to narrow the chair a little at first.

Adjustment of backrest
1. To raise the backrest, pull it upwards.
2. To lower the backrest, squeeze together the metal prongs of the friction clip, and push the backrest down.

Adjustment of headrest
1. To raise or lower the headrest, unscrew the lower knob, push or pull the headrest to the required height, and tighten knob.
2. To adjust the angle of the headrest, unscrew the upper knob, move the headrest to the desired angle and tighten the knob.
Preparing support system for occupant

1. Set backrest and headrest to the approximate required positions.
2. Remove air tube plug from cushion (under front of seat)
3. Spread beads in cushion evenly over seat and back surfaces.
4. Smooth out upholstery.
5. Sit occupant in chair.
6. Readjust backrest and headrest if necessary.
7. Ensure that cushion fits occupant snugly.
8. Fit hand pump to air tube.
9. Pump out air.
10. Replace plug, being careful not to let air back into the cushion.

To change posture, remove air tube plug, and repeat 6 - 10.

IMPORTANT

If the cushion is punctured, it will not work as it is intended.

Punctures can be mended with Sellotape.
SPINA BIFIDA SUPPORT
EVALUATION OF SUPPORT SYSTEM

a) Mechanics of system
1. Upholstery
2. Cushion
3. Headrest adjustment
4. Backrest adjustment
5. Support to wheelchair fitting
6. Tray
7. Armrests
8. Footrests
9. Brakes
10. Overall size, shape, weight
11. Safety
12. Convenience
13. Cleaning

b) Operation of system
1. Pushing
2. Feeding
3. Transfer into and out of the chair
4. Use on floor
5. Alterations in day to day routing
6. Limitations of use
7. Appearance
8. Use with car etc.
EVALUATION OF SUPPORT SYSTEM : CHILD'S ACTIVITIES

1. Self propulsion

2. Increase in range of activities

3. Limitation in range of activities
Notes on evaluation of the body support system

1. The list provided under the heading of Day to Day Handling contains suggestions of some of the aspects of the wheelchair and support system you may wish to comment on. It is not necessarily a complete list: you may find there are other aspects worthy of comment. We should like to know if the system does the job of providing support and mobility that you expect it to: whether all or any part is difficult or inconvenient, or particularly satisfactory. Please be as candid as possible in your assessments, as this will help with future applications.

2. Please comment on any increase or limitation the wheelchair and support system have made to Lisa's activities, and whether she has tried to propel herself, and with what result.
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**BINOMIAL PROBABILITY**

- **MEAN**: Indicates the expected mean value for the binomial distribution.
- **SD**: Standard deviation of the binomial distribution.
- **T**: T-statistic calculated based on the difference between the observed and expected values.
- **PROB**: Probability value associated with the calculated T-statistic.
- **DF**: Degrees of freedom for the t-distribution. The t-distribution is used to determine the probability value.
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