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The design of attendant propelled wheelchairs

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Abstract

The attendant operated wheelchair is propelled by applying forces to handles at the rear of the chair. There are no published data to justify the design of pushing handles on existing wheelchairs. In Dundee, studies of pushing have been conducted in order to obtain subjective preferences for location and design of handles and an understanding of biomechanical factors associated with wheelchair pushing.

Preferred positions for handles have been found to be in the region of 0.75 of shoulder height, 1.14 times shoulder width although deviations of ±5% in these values are still rated as acceptable. The preferred positions do not correspond to minimum levels of resultant force or with lowest levels of moment in any of the upper body joints. Moments occurring at the lower back are not substantially affected by handle position. The biomechanical analysis so far has not revealed why some handle positions are more comfortable for pushing than others. Further study, involving calculation of resultant moments (rather than just sagittal plane moments) at these joints and at the lower body joints, is a next step in attempting to find the indicators of discomfort.

Transferring a patient from or to a wheelchair can be a difficult operation with risks of accidents to the patient through falling and risks to the attendant of strain, particularly to the back. Current footrests on wheelchairs are a major source of the problems during transfer. A new approach to footrest design is described which solves these difficulties by using a footrest that lowers onto the floor. This has other attractive features such as providing good stability and restraint of the chair during transfer. The armrests are also discussed since they have a role to play where patients can assist themselves during transfer but have the potential for being an obstruction when patients need to be lifted from wheelchairs.

The ease of pushing and manoeuvring, the difficulties caused by obstacles such as carpet edges and lift entrances, the operation of the brakes, and the position of the pushing handles are all important aspects of chairs used for transporting patients. The wheels, particularly the wheel diameter, tyre compressibility and castor trail, are determinants of the mobility aspects. However, the position of the wheels in relation to the centre of gravity and whether the castors are at the front or rear must also be considered. The brakes, as well as being effective, should be easy to apply and not too affected by wear. A prototype wheelchair is described which incorporates design features suggested by research into the above considerations.

Introduction

Attendant propelled wheelchairs are used indoors and outdoors by domestic users, and also in hospitals and institutions to transport patients who are too unwell to walk. Those used in the domestic environment are intended to carry disabled or elderly occupants who are not capable of using a self-propelled wheelchair, and who may not be able to operate or cannot afford a powered chair. Attendants are usually a family member or close friend of the occupant. Many attendants, such as husbands or wives, are elderly themselves and

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may be enfeebled, others are parents of disabled children and adults. They frequently experience difficulties with pushing and manoeuvring their wheelchairs — especially outdoors — and with transferring the occupant into and out of the chairs. In the hospital setting wheelchairs are used by nursing staff to transport patients locally within the ward area and by porters to carry them to the various hospital departments for treatment. This again involves transferring patients into and out of the chairs, a process which can be very arduous for the attendants, who will be moving many patients each day. It is important then that attendant propelled wheelchairs are designed for making propulsion and general operation as easy as possible for the operator by minimising the physical demands placed on the attendants.

This paper commences by reviewing studies of the biomechanics of attendant propulsion, a subject which has not been investigated in great detail compared with self-propulsion. It will then discuss the two principal concerns for the attendant — patient transfer and mobility of the wheelchair — and the design features which relate to them. A review of the different types of attendant wheelchairs in domestic and hospital use will be given at the end of the paper, to illustrate the range and application of the models available.

Biomechanics of attendant propulsion

In order for a wheelchair to be driven, steered and manoeuvred with ease, its rolling resistance and turning resistance should be low and the mode of propulsion should be optimised biomechanically to maximise comfortable operation of the chair. A biomechanical study of attendant propulsion of wheelchairs is in many respects less complex than that for occupant propulsion; there is no need to investigate effects of users' disabilities, different methods of driving the chair (such as handrim or lever propulsion), or influences of the relative position of the occupant and the drive handle on the efficiency of propulsion. The attendant wheelchair simply incorporates handles located at the rear of the chair which are used to control all propulsion and manoeuvring operations. The position of the handles (their height, separation and shape) affects the load distribution on the wheels while driving the chair, the posture and comfort of the attendant and the biomechanics of propulsion. These points will be discussed below. Biomechanical studies to date have only included pushing. Pulling, turning and other manoeuvring have not yet been investigated. The discussions in this section are based on work reported by Abel (1988).

Mechanics of propulsion

Figure 1 shows a horizontal force F_h being applied to a wheelchair in order to maintain its speed against a rolling resistance R. The rolling resistance occurs at ground level, i.e. at the contact region between the wheel surface and the ground over which it is travelling. If a horizontal pushing force is applied to the handles at a height above ground level a turning moment will be generated which transfers a proportion of the weight of the occupant and chair from the rear wheels to the front wheels. This will make the chair more difficult to push if the rolling resistance for the front wheels is greater than that for the rear wheels. The magnitude of this effect is shown below to be small.

For wheelchair wheels running on hard surfaces, rolling resistance is approximately proportional to the vertical load carried by the wheel (Frank and Abel, 1990), the ratio of the resistance force to the vertical loading being the coefficient of rolling resistance μ . Referring again to Figure 1, the ratio of F_h required to propel a vehicle with handles at a height h above the ground, to the horizontal force F_g (=R), which would be required at ground level, may be shown to be equal to $L/(L-h\,\delta\,\mu)$, where $\delta\mu$ is the difference between the coefficients of rolling resistance of the front and rear wheels (i.e. $\mu_f-\mu_r$) and L is the wheelbase. This ratio is unity for most models of attendant propelled wheelchairs designed for use in hospitals since they use the same types of front and rear wheel (i.e. $\delta\mu=0$). For outdoor attendant propelled wheelchairs, which have front castors that are smaller than the rear fixed wheels, typical values for L, h, μ_f and μ_r are 0.4m, 0.95m, 0.045 and 0.02 respectively. These figures give a value if F_h/F_g of about 1.05, i.e. the attendant propelled wheelchair requires about 5% more force than an equivalent self-propelled wheelchair with the same weight distribution on the wheels, to propel it at constant speed. It has been found that the preferred height for pushing handles is about 0.73 to 0.74 of shoulder height (0.6 of stature) which, for the middle 90th percentile of the British male and female populations, is in the range 0.90 to 1.10m (Abel, 1988). The change in the ratio F_h/F_g over this range (which includes the heights of handles on most current attendant wheelchairs), is only about 1%. This effectively means that handle height can be selected for user comfort without affecting the magnitude of the force required to push the chair.

Efficiency of pushing

When attendants push against the handles of wheelchairs, and other similar vehicles, they do not push directly forwards — there is a tendency also to lean on the handles, producing a resultant force which is inclined downwards. Leaning on the handles adds to the vertical loading on the wheels and therefore also the rolling resistance. An efficiency of propulsion E_α may be defined as the ratio of the force required to push the wheelchair forwards when the resultant force, F, is inclined at an angle α downwards (Fig. 1), to the force required to push the chair when the resultant force F_h is horizontal (in the direction of motion). E_α may alternatively be expressed as 1-μtanα, assuming all four wheels to have the same coefficient of rolling resistance, an assumption which has little effect on the calculation and is anyway generally true for hospital wheelchairs. Graphs of E_α against α are drawn in Figure 2.

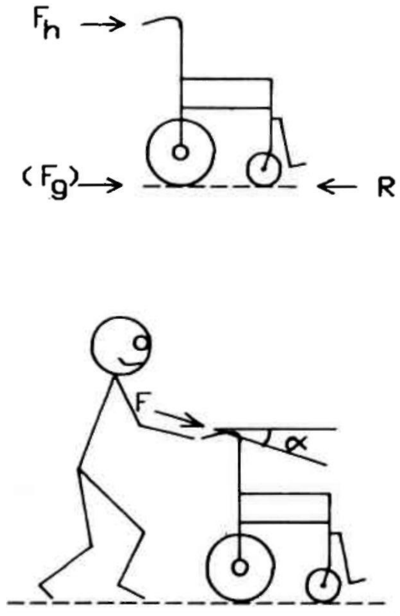

Fig. 1. Pushing forces.

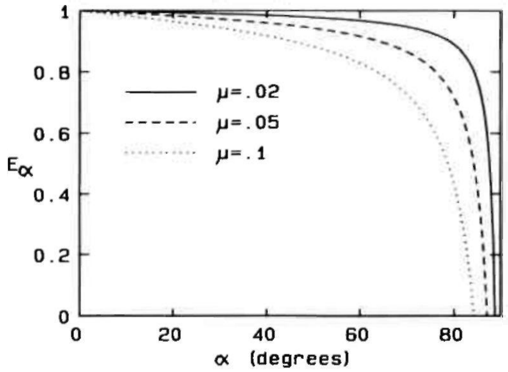

Fig. 2. Pushing Efficiency (Eα) versus Downwards Pushing Angle (α).

The relationship between α and handle height (normalised to an individual's shoulder height) has been found to be approximately linear (Fig. 3). This shows an example based on experimental data from 6 subjects pushing 1kg (best straight line to the data is drawn) and 4kg (data points also shown) horizontally against a fixed horizontal crossbar while walking on a treadmill at 1m/s. These pushing forces correspond to light and heavy pushing conditions for wheelchairs and represent respectively coefficients of rolling resistance corresponding to a best case of 0.02 and a very bad case of 0.1. These two graphs also illustrate the general case that, for a given handle height, the angle α decreases as the pushing force

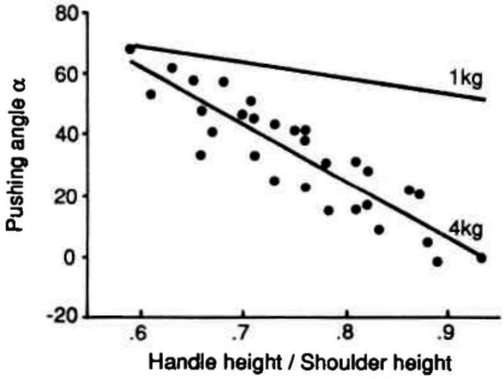

Fig. 3. Downwards Pushing Angle (α) versus Handle Height.

increases. This implies that a high rolling resistance gives rise to a low downwards pushing angle. The values for α from Figure 2 corresponding to the preferred handle heights of 0.73 to 0.74 of shoulder height when projected on to the graphs of Figure 3, give values of E_α of greater than 0.94 in the most unfavourable case. Designing wheelchairs with handles at the preferred height for attendants will not significantly affect the wheelchair's ease of propulsion.

Joint moments

The effect of handle height on the moments generated at the shoulder and the lumbosacral back joint in the sagittal plane has also been investigated for dynamic pushing, these joints being of interest because subjects during pushing tests noted discomfort in the shoulder area while pushing against a high handle, and because the lumbosacral area is particularly prone to injury from manual handling tasks (such as lifting). Figure 4 illustrates postural differences between pushing against a high and low handle. Interestingly, the magnitude of the moments at these joints has been found to be low at both high and low handle heights. The resultant pushing force vector passes close to the shoulder joint (S), producing a low turning moment, even taking the weight of the arms into account. The lumbosacral joint (LS) moments are also low in magnitude, the turning moment created by the pushing force being balanced to a large extent by that created in the opposite direction due to the weight of the trunk. This was generally found to be the case throughout the range of pushing forces, the pushing subjects adapting their postures to reduce shoulder and lumbosacral joint moments. A more extensive biomechanical analysis, including calculation of moments generated in the other reference planes, would therefore need to be conducted in order to identify the important joint moments for correlating comfort or discomfort of pushing with the height of the pushing handles.

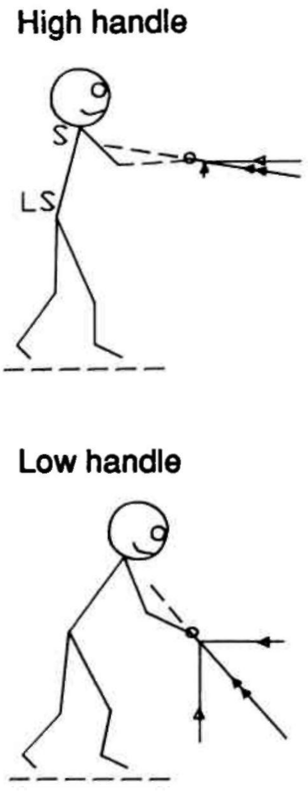

Fig. 4. Pushing posture.

Turning a wheelchair

The turning resistance of a wheelchair may be defined as the torque, or turning moment, required to turn the wheelchair in its smallest circle, which for a typical wheelchair with two castors and two fixed wheels has a centre halfway between the two fixed wheels. The magnitude of the torque is influenced by the castor trail of the wheelchair's castors, the friction generated between the fixed wheels and the ground as the wheels slide over it, and the positioning of the castors with respect to the centre of rotation of the wheelchair. The magnitude of the turning force which the attendant must exert is equal to the value of this torque divided by the distance from the centre of rotation of the chair to the operating handles. Since the handles of attendant propelled wheelchairs are always at the rear of the vehicle, chairs with rear castors will require less handle force for the same turning torque than those with front castors since the distance from the handles to the centre of rotation of the wheelchair is greater. There have been no specific biomechanical studies on the process of turning and manoeuvring attendant propelled wheelchairs. It would be difficult to design experiments which would cover the wide variety of manoeuvres which are made.

Subjective studies on the preferred location of castor wheels have however been undertaken, the conclusions of which will be presented in the next section.

Design features of attendant propelled wheelchairs

The occupants of attendant propelled wheelchairs are affected directly by the comfort offered in terms of seating, posture, ride comfort and various chair dimensions. The attendants, however, are confronted with the problems of transferring patients to and from the chairs and with the difficulty of pushing and manoeuvring the chairs. It is these two aspects, transfer and mobility, and the design features of wheelchairs that relate to them that are considered here. Research into attendant propelled wheelchairs carried out over several years in the School of Biomedical Engineering in Dundee University provides some of the background for the following discussion.

Patient transfer

The main components of the wheelchair which determine the ease of patient transfer are the footrests, armrests and brakes. These are considered in turn in the following.

Footrests

Footrests are essential on wheelchairs but they add considerably to the difficulty of transferring patients into or out of them. The process of removing the footrests from under the feet of a patient prior to transfer out of the chair (or the reverse procedure following transfer into the chair) carries risks of injury to the patient and risks to the attendant of strain, particularly to the back.

Some hospital wheelchairs have fixed footrests. These cause difficulties because patients either have to stand up on the footrest and then step down onto the floor from it, or they have to place their feet on the floor ahead of the footrest which makes standing up difficult because there is a large horizontal distance between the seat and the patients' feet. In the first case patients could fall while in the second case patients may have insufficient leg length to reach the floor and, even if they have, a very large lifting force is required from the attendant to get them standing vertically. The remaining hospital chairs and the domestic chair supplied by the National Health Service in the United Kingdom require the patients feet to be lifted and the footrests to be swung or slid away before placing their feet on the ground and helping them to stand. It is not uncommon for the patient's condition to be such as to make this procedure very difficult to carry out; attendants often have to kneel on the floor to accomplish it successfully.

Research in Dundee has been aimed at gaining a better insight into the footrest problem and producing improved designs (Frank and Abel, 1990). In an initial study, several different footrests, including some novel designs, were assessed by nursing staff in a variety of hospital wards. It was found that an elevating type of footrest was highly favoured above others. This footrest consisted of a single thin plate that could be lowered to, or raised from, the floor by means of a foot-lever operated by the attendant. In one of the wards (neurological) it was observed that nurses tending certain patients had severe difficulty with any of the footrests except the elevating type. The most immobile patients required two nurses to kneel on the floor in order to swing the patients legs forward and move the footrests into place.

Following this investigation into footrests on ward chairs, a similar study using porters' chairs was carried out. The elevating footrest was as favourable amongst porters as it had been with nurses. As a result of these studies a prototype wheelchair was constructed with an elevating footrest as the starting point of the design. A latching strut was utilized to hold the footrest in the raised position and the attendant was able to control the lowering as well as the lifting of the footrest.

In this particular design the front end of the chair, to which the footrest is attached, is raised using the front wheels as a fulcrum (Fig. 5). Other, perhaps more complex and costly, mechanisms could be used. For example, the footrest alone could move using a vertical slide or four-bar-link mechanism, or the chair and attached footrest could recline about an axis under the seat. A different approach to the footrest problem could be to retain the present type of footrest that folds or slides out of the way and devise a means for raising the patient's legs together or in turn. For example, the seat and back of the chair could recline so lifting the patient's feet clear of the footrests.

Armrests

The armrests of attendant propelled wheelchairs have to meet two main requirements where transfer is concerned: they should be correctly positioned to allow patients with good arm strength to assist themselves in rising, and they should be removable to allow the more disabled patients to be assisted or lifted from the chair. The prototype wheelchair produced in Dundee was constructed with armrests that protruded well forward, to give good support for the patient's hands when rising and which coud be folded down at the side of the chair to allow side transfers and good access when a patient needed to be lifted from the chair (Fig. 6). All the nurses and porters who assessed the prototype chair commented favourably on these armrests. A further advantage is the ability to fold away the armrests rather than having to remove them, which would leave the attendant holding the armrest and possibly having to leave it separately from the chair with the risk of it becoming lost.

Brakes

It is very important for a wheelchair to remain stationary and stable during patient transfer, particularly when patients transfer themselves or assist the attendant by utilising the armrests. Attendant propelled wheelchairs in hospitals generally have castored wheels at the rear of the chair (because fixed front wheels permit the use of a larger footplate) incorporating brakes which rotate with them. It is often the case that the chair will have been stopped with the castors in a position that makes the brakes awkward to apply. Another problem encountered with this type of brake is that it can become ineffective when wear has taken place. The brakes on the domestic attendant propelled chair supplied by the National Health Service in Britain act on the tyres and are applied by levers low down on the sides of the chairs. These brakes become ineffective when the tyres are below the proper pressure, a frequent occurrence (Abel et al., 1988). Also they are not easily accessed by the attendant.

Making the brakes reliable and easy to use increases the safety of a wheelchair when it is parked with an occupant present and during transfer operations. The work in Dundee produced an improved braking system for hospital wheelchairs (Fig. 7) in which the brakes on both rear wheels were applied simultaneously by a single foot-lever that was accessible from the rear and the sides of the chair. Because the brake was applied to the tyre by a rod passing down the centre of the castor

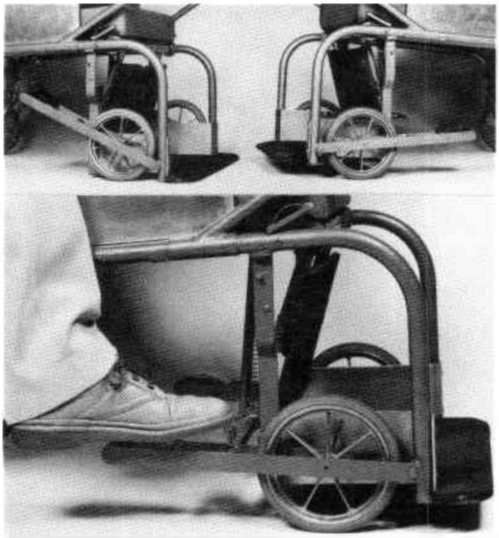

Fig. 5. Footrest design. Top, in raised and lowered position: Bottom, operation of mechanism.

Fig. 6. View of chair showing folded armrests and improved design of pushing handle.

pin, it could be applied with the castor in any position. In addition, a relatively long spring was used to hold the brakes on, with the result that very little reduction of brake effectiveness occurred when wear of the tyre and brake parts had taken place.

A secondary but very valuable aspect of the elevating footrest described above is that because the patient stands on the footrest, thus pressing it onto the ground, the chair is automatically well braked and completely stable during transfer operations. If nurses and porters were required to lower such a footrest whenever a chair was parked or a patient transferred, a normal brake for the chair could perhaps be dispensed with.

Mobility

The ease of pushing and manoeuvring, the difficulties that obstacles such as carpet edges and lift entrances cause, and the position of the pushing handles are all important aspects of chairs used for transporting patients.

The ease of pushing in a straight line on any given surface depends on the rolling resistance of the wheels and is particularly important where long distances may be travelled. Generally, rolling resistance decreases with wheel diameter and increased tyre hardness. Pneumatic tyres, however, have a lower rolling resistance than tyres of equivalent size made from soft rubber or polyurethane (Frank and Abel, 1989). There is a negligible contribution to rolling resistance from ball or roller wheel bearings whereas journal bearings may add to it by up to 50% (Frank and Abel, 1989). Pneumatic tyres would be inconvenient and unnecessary on hospital chairs but the combination of light weight, good shock absorption and low rolling resistance makes them more attractive for the folding type outdoor chair. The reason for not using cheap small wheels with hard tyres on hospital chairs is that both these factors make the chair very much more prone to being impeded or stopped by small steps such as carpet edges or the misaligned levels that often occur at the entrance to lifts (Frank and Abel, 1989).

Castor trail (the horizontal distance between the wheel axis and the axis of the castor bearing) is significant in that the greater it is made the less prone the castor will be to shimmy (rotational vibration) and the easier it will be to turn the wheelchair when starting from rest. Work carried out at the University of Virginia (Kauzlarich et al., 1984) has shown that wheels with a low moment of inertia about a diameter (i.e. lighter wheels) are also less prone to shimmy.

Chair manoeuvrability depends on several factors and is obviously important in hospital ward areas. Studies of manoeuvrability have been carried out in Dundee by using test

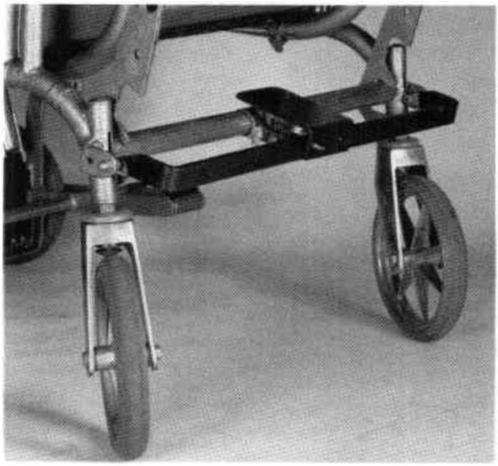

Fig. 7. Improved braking system.

Fig. 8. A chair with wheels just behind the centre of gravity.

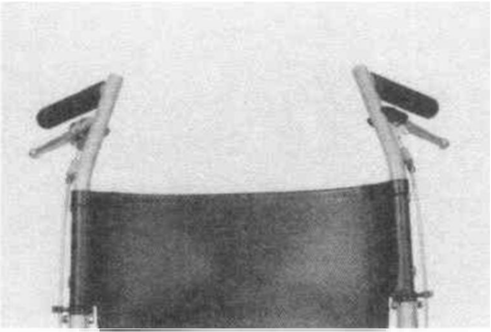

Fig. 9. Handle position on domestic chair.

circuits and mazes and by measuring wheelchair turning forces. The mazes consisted of routes along which the volunteers pushed a variety of occupied wheelchairs. The number of bumps, stops and reverses were counted and the volunteers were asked to give subjective comments. The results indicated that the most manoeuvrable chair is one where the fixed wheels are as near to the centre of gravity as possible. This also reduces turning forces to a minimum. An example of a chair constructed with the fixed wheels just behind the centre of gravity is shown in Figure 8. It can be seen that a pair of small rear wheels, which are not touching the ground, have been added to prevent the chair tipping over backwards. The study showed that front castors generally give better manoeuvrability than rear castors. However, subsequent studies in hospitals did not confirm the desirability of front castors. Porters, especially, preferred rear castors, probably due to the fact that chairs have to be pulled, rather than pushed, through the numerous swinging doors (fire doors, ward entrances etc.) that are found in hospitals.

The positions of the pushing handles currently used on attendant propelled wheelchairs are determined by mechanical convenience rather than ergonomic principles; they are either in the form of a horizontal cross-bar at the rear of the chair or a pair of backward pointing handles extending from the chair back. The results of the pushing studies described earlier suggest that current handles are too low and incorrectly angled for comfort. A handle designed for hospital wheelchairs using the results of the pushing studies can be seen in Figure 6. User trials of this handle indicated that not only is it comfortable when pushing but also it allows single handed pushing or pulling (because the handle can be held centrally) and it makes the chair easy to turn when the attendant approaches the chair from the side. A similar handle position could also be achieved on the domestic chair as demonstrated by the example show in Figure 9.

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