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Biomechanics and the wheelchair

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Abstract

Wheelchair biomechanics involves the study of how a wheelchair user imparts power to the wheels to achieve mobility. Because a wheelchair can coast, power input need not be continuous, but each power strike can be followed by a period of recovery, with the stroking frequency depending on user preferences and the coasting characteristics of the wheelchair. The latter is described in terms of rolling resistance, wind resistance and the slope of the surface. From these three factors the power required to propel the wheelchair is determined, and must be matched by the power output of the user. The efficiency of propulsion is the ratio of this power output to the metabolic cost and is typically in the order of 5% in normal use.

The features required in a wheelchair depend upon user characteristics and intended activities. The ideal wheelchair for an individual will have the features that closely match these characteristics and activities. Thus prescription is not just choosing a wheelchair, but choosing the components of the wheelchair that best serve the intended purpose. In this paper, each component is examined for available options and how these options effect the performance of the wheelchair for the individual.

The components include wheels, tyres, castors, frames, bearings, materials, construction details, seats, backrests, armrests, foot and legrests, headrests, wheel locks, running brakes, handrims, levers, accessories, adjustments and detachable parts. Each component is considered in relation to performance characteristics including rolling resistance, versatility, weight, comfort, stability, maneouvrability, transfer, stowage, durability and maintenance. Where they exist, wheelchair standards are referred to as a source of information regarding these characteristics.

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Introduction

In recent years many variations in wheelchair design and construction have become available. Thus for a given user there may be several options to choose from. Based on the physique of the user, the intended usage and the funds available, it should be possible to make an appropriate selection of design features and optional components that constitute the ideal wheelchair. The process of selection is one of matching features to requirements and to do this logically it is necessary to be knowledgeable in the relative merits of the various component designs and materials and to assess the capabilities of the user together with the environment and intended usage.

The first section of this paper deals with user capacity based on biomechanical studies. From this, it is possible to estimate the importance of seating position with respect to the hand rims and its effect on the stroke length and propulsion efficiency. Studies also include the work capacity of individuals and how this indicates performance in different environmental conditions such as hills, head winds and side slopes, and the influence of the balance of the wheelchair on propulsion effort. A discussion of the value of alternate drive systems such as cranks and levers is also included.

Correspondingly, the design and construction of the wheelchair and its component parts can have a marked effect on the performance, energy requirements and durability under various ambient conditions and use patterns. With a large variety of users, usage, and products, it is obvious that there is no one wheelchair for every user, but knowledge of the performance of each tyre of component part and each material can help in a logical selection. In many cases, the newly created International Standards Organisation's (ISO) Wheelchair Standards will disclose the necessary information. In other cases, some general rules can be presented to assist in decision making. This will be explored in the section on design characteristics.

Biomechanics

Much of the work on wheelchair biomechanics has been concerned with efficiency of propulsion, or in other words a measure of the effort required to do a certain amount of work. Unlike walking or running, the amount of work required to propel a wheelchair is readily measured and is dependent upon the rolling resistance of the wheelchair, the effect of ramps, side slopes and wind resistance. These will be discussed in the section on design characteristics. In the laboratory, this work can be simulated on a dynamometer.

Several things can be learned from efficiency experiments, such as the efficiency of a wheelchair compared to other means of mobility, and the effect of the design of the wheelchair on the efficiency. Brubaker et al., (1981) tested a number of athletes, and non-athletes, all wheelchair users to determine not only efficiency, but, also maximum work output. The maximum work output recorded on an athlete was 125 watts (W) with an efficiency of 13.9% (Table 1). This remarkable achievement is approximately 1/6 horsepower. For comparative purposes it is better to record the power per kilogram (kg) of body weight, and the maximum in this case was 1.88 W/kg with a 13.0% efficiency. The non-athletes, showed a much lower level and a correspondingly lower efficiency (Table 2). For a typical user on level ground, efficiencies as low as 3% are not unusual. Similar studies have shown that efficiency is higher for higher work loads and for lower speeds. A series of experiments using both normal and disabled persons showed that for a work rate of 0.4 W/kg efficiency averaged 9% at 3 kilometres per hour (km/h) and 10.3% at 2 km/h. For a work load of 0.2 W/kg and the same speed tests the efficiency dropped to 7.1% and 8.4% respectively. These studies give real evidence that for persons with a good arm function, gearing could be a real advantage to increase speed without increasing the effort.

It is interesting to compare the work output and efficiency with that obtained in pedalling. In preparation for a pedal powered flight from Crete to Tira, 118 km, athletes were tested by Nadel and Bussoleri (1988) for exercise bouts up to four hours duration. The results indicated a continuous work output of 5.25 W/kg with efficiencies ranging from 18% to 34%.

Of practical interest to the wheelchair user, is how can the design improve efficiency. Studies by Engel and Hildebrand (1974) showed that levers moved back and forth to drive the wheels could increase the efficiency compared to handrims.

Similar studies by Brattgard et al., (1973) indicated that cranks also were more efficient than handrims. Unfortunately there are practical difficulties associated with both levers and cranks which increase cost, weight and complexity. The crank studies were conducted using bicycle type cranks mounted in front of the user — a juxtaposition that is mechanically difficult and socially undesirable for the user. Typical lever systems rely on connecting rods to drive the wheels. This causes difficulties in manoeuvring and in starting, particularly on slopes. Brubaker

Table 1. Maximum performance data for national calibre wheelchair athletes.

Subject	Disability	Sex	Wt (kg)	VO_2 (Rest)	VO_2 (Max)	Energy Cost (watts)	Power Output (watts)	Power Output (watts/kg)	Efficiency (%)
KJ	T10	F	49.9	0.19	1.31	394.8	41.7	0.84	10.6
GL	SB	F	35.4	0.17	1.33	408.9	34.7	0.98	8.5
CB	T3	F	44.9	0.18	1.41	443.6	41.0	0.91	9.5
SR	T12	F	57.2	0.20	1.68	521.7	62.6	1.09	12.0
GM	T10	M	80.0	0.28	2.84	902.0	125.0	1.56	13.9
FM	C5-7	M	80.6	0.28	0.95	234.4	30.8	0.38	13.1
FY	C6+	M	58.1	0.20	0.95	255.6	29.2	0.50	11.4
BH	Polio	M	59.1	0.21	2.55	824.9	111.1	1.88	13.0

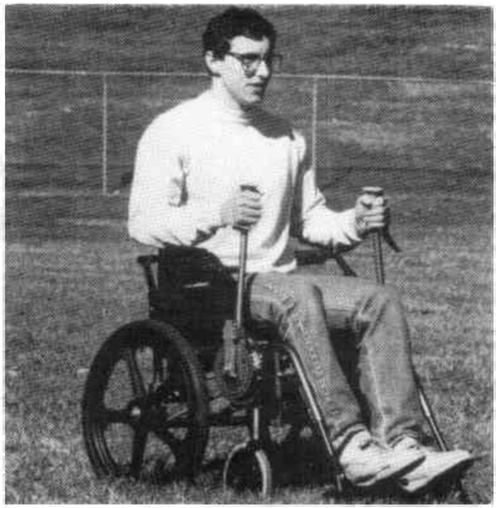

Fig. 1. Experimental lever drive system fitted to a commercial wheelchair. A clutch is operated on each stroke by inward force on the lever. allowing the user to stroke forward, reverse or apply brakes as required.

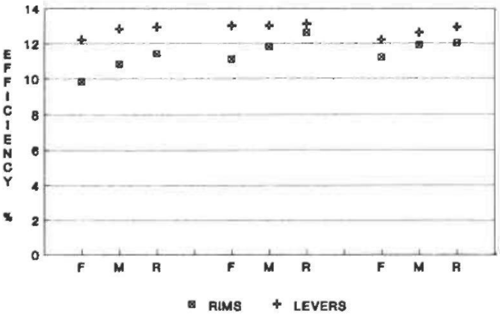

Fig. 2. Results of testing rims and levers at the same speed and load for nine seat positions. Note that the efficiency for levers was nearly independent of seat position and somewhat greater than that for handrims.

and McLaurin designed a single acting lever system that overcame these problems (Fig. 1) and subsequent tests with single acting levers, that is levers that produce a driving force in only one direction, were tested. The results of the testing indicated an increase in efficiency as compared with rims (Fig. 2).

It was stated earlier, that gearing could increase efficiency. Another consideration is seat position with respect to the handrims or the levers. Studies (Brubaker et al., 1984) with six normal and six disabled subjects at the University of Virginia (UVA) indicated that moving the seat with respect to the axle has a considerable effect using handrims, but little effect using levers. It should be noted that the conventional position with the backrest directly above the axle is not ideal for maximum efficiency.

Table 2. Wheelchair performance data for non-athletes using the wheelchair dynamometer.

Subject	Lesion Level	Relative Load (watts/kg)	Absolute Load (watts)	Efficiency (%)	Heart Rate	Speed (kmph)	VO_2 Max (l/min)
LM (F)	L1-2	0.52	27.3	10.0	171		1.29
WW (M)	T4	0.48	40.9	7.9	150		1.46
JG (M)		0.81	72.9	8.0		3.5	2.96*
CB (F)		0.20	10.9	5.1	130	3.0	0.88
		0.25	13.6	5.5	139	3.0	1.02
		0.40	21.7	6.8	150	3.0	1.12
AS (F)		0.20	10.4	6.4	115	3.0	0.67
		0.25	13.0	6.8	118	3.0	0.79
		0.40	20.7	7.8	144	3.0	1.01
RC (M)		0.20	16.4	7.8	90	3.0	0.98
		0.25	20.5	9.3	95	3.0	1.01
		0.40	32.7	0.3	110	3.0	1.29
DM (M)		0.20	15.0	7.5	89	3.0	0.87
		0.25	18.8	7.8	103	3.0	1.00
		0.40	30.0	8.9	107	3.0	1.29
TS (M)		0.20	20.9	9.0	77	3.0	1.01
		0.25	26.1	10.4	87	3.0	1.08
		0.40	41.8	10.5	104	3.0	1.50

* Maximum Value

The reason that seat position affects efficiency is found in the mechanics of the arm during the power stroke and recovery. The optimum seating position is primarily dependent upon the position of the shoulder joint with respect to the axle, and the dimensions of the arm segments. This determines the geometry of the joint position and the range of motion of the muscles used in propulsion.

Arm motion has been studied at the UVA on the wheelchair dynamometer previously referred to, with the addition of a set of four instrumented wands attached to the wrist, near the elbow, near the shoulder and at the base of the cervical spine. Each wand is attached to three potentiometers which continuously record the angle of the wand in space and its length from its reference base to the body attachment (Fig. 3). A computer programme converts this information to the position of the neck, shoulder, elbow and wrist with respect to the wheelchair rim.

Data from this arm position instrumentation can be plotted to illustrate motion during a propulsion stroke (Fig. 4) along with the associated input torque. It is interesting to note that only a part of the forward motion is effective in driving the rim. During the early part of the stroke, the hand is accelerating to the speed of the rim. After rim contact, the hand continues to accelerate, providing input torque to the rim. After releasing the rim, the hand begins to decelerate before beginning the return stroke to the starting position.

The pattern of the stroke varies with seat position (Fig. 5). When the seat is high, the stroke is shorter because the hand cannot reach as far down the rim. When the seat is forward, the stroke acts on the forward part of the rim, and when the seat is to the rear it acts over the top of the rim. A low seat allows a longer stroke over a large section of the rim. This means that the force input can be lower than for a high seat where the energy must be applied in a shorter time. However, for the higher seat position and shorter stroke, a higher frequency is possible since the time for the power stroke is less and the return to the starting position is shorter.

The return or recovery stroke is worth considering. Even though no energy is imparted to the rim at this time, energy is required to move the arm backwards to the starting position. With a low seat, the elbow must be flexed for this action. With a high seat, this flexion is minimized, thus reducing the required energy. It has been postulated that one reason why levers are more efficient than handrims, is that the weight of the hand and forearm rests on the lever and hence less energy is needed for the return stroke.

Experienced and athletic wheelchair users often use a low stroke frequency when cruising. In

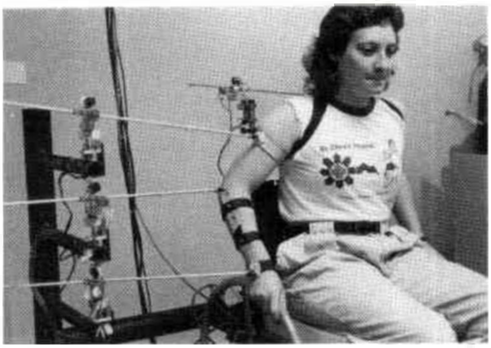

Fig. 3. A subject on the dynamometer with wands attached to the arm and base of the cervical spine. Three potentiometers on each wand provide information from which the shoulder, elbow and wrist positions are determined.

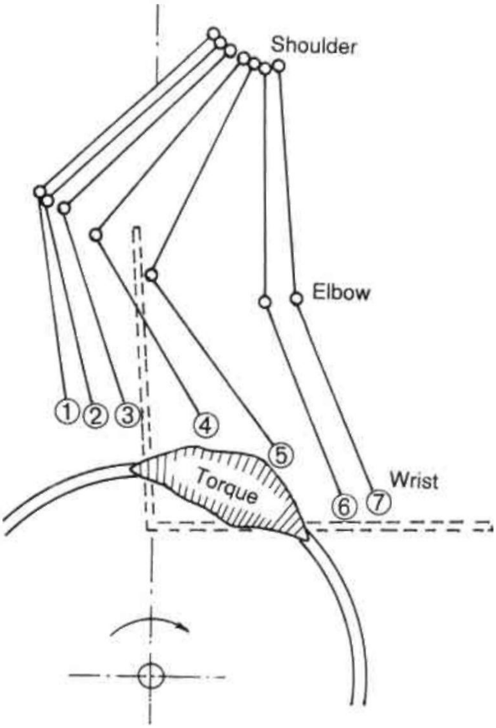

Fig. 4. Stick diagram of a typical forward stroke for a seat in the position shown. The segments are depicted at 1/10s intervals. Note that torque is applied during only three of these seconds.

this case, greater force is applied to the handrim during the power stroke, thus accelerating the wheelchair to a greater extent. This allows the wheelchair to coast further before the next power stroke is required. Under these conditions the return stroke is much like a leisurely pendulum swing, requiring little effort. With low frequency stroking a wheelchair with low rolling resistance becomes increasingly important so that it does not slow down appreciably between strokes. Measurements of the torque input and the associated variations in wheelchair speed illustrate the changing speed during power input and recovery (Fig. 6).

For racing, handrims are smaller in diameter. For a 27in (524mm) wheel they may be as small as 15in (381mm) or even 12in (305mm). The reason is to gain mechanical advantage or more correctly speed advantage. Pushing on a 15in handrim on a 27in wheel at 5 kmph will produce a speed of $5 \times \frac{27}{15}$, or 9 kmph. Since wheelchair athletes may travel at a speed of up to 25 kmph and there is a practical limit to the speed of muscle contraction (approximately 10 × muscle length per second) it is not difficult to see the importance of small diameter handrims for racing.

In order to reach small diameter handrims, the seat must be lowered, and the wheels cambered (tilted inwards at the top) to permit the arms to reach comfortably over the wheels.

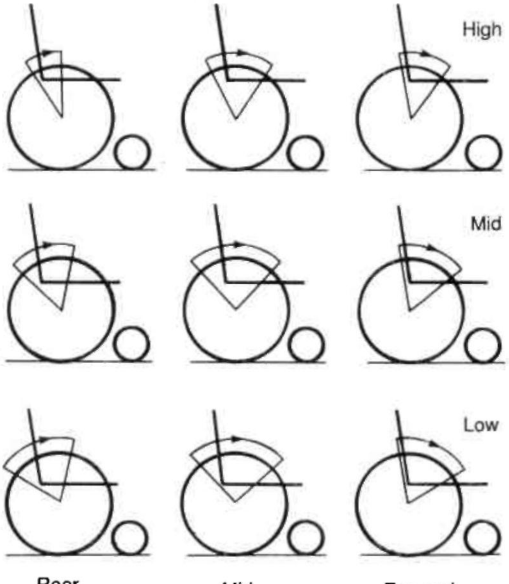

Fig. 5. The grasp and release position during the forward stroke is shown for nine seat positions.

When stroking the handrims at higher speeds, there is insufficient time for the hand to grasp the rim. Typically the stroke force is applied by friction between the rim and the thumb and forefinger which raises large callouses. A friction surface on the rim will reduce the pressure required to drive the rim forward. A friction surface also makes propulsion easier for those with weak or impaired hands. Unfortunately the friction surface is too effective when the handrims are used for braking, causing severe skin damage when braking from high speed or down a steep hill.

The cross-section shape and size of the handrim can also have some effect. Typically a handrim is made from round tubing about 16mm in diameter. Smaller diameters are difficult to grip while larger diameters, up to 25mm may be more comfortable. A wheelchair user in California designed and used a rim with an egg-shaped cross-section with an average diameter of about 25mm (Farey, personal communication). Based on this experience, the UVA laboratory tested several, about this size, and although the results were scientifically inconclusive, the subjectively preferred shape was elliptical in section with the long axis canted at about 20° to the vertical, very similar to Farey's design. The 20° angulation could be either inwards or outwards, according to preference.

Tanaka (1982) and Brubaker and Ross (1988) have studied muscle activity during simulated propulsion using electromyography. Surface electrodes placed at or near the motor points of arm and shoulder muscles recorded the muscle activity associated with each part of the stroke.

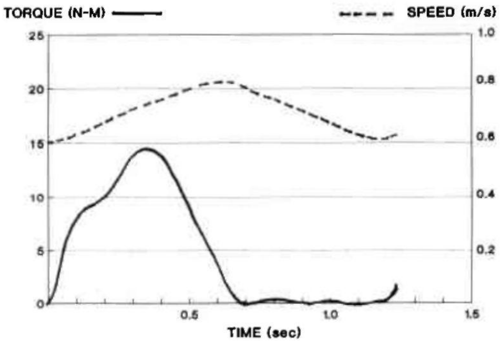

Fig. 6. A typical torque curve for one complete cycle showing the resulting speed (upper curve) of the wheelchair. At higher speeds, the curve becomes much higher and acts for a shorter period of time.

The marked difference between the muscle activity of a person with normal arm musculature during a lever drive exercise for three seat positions (Fig. 7) is typical of the variations that occur and for this reason, EMG studies have not yielded very useful information to date.

Design characteristics

With an understanding of the human factors in wheelchair mobility, it should be possible to assemble a wheelchair that best suits an individual, but first it is necessary to examine the technical characteristics of the various components and their influence on the overall design. Having assessed the ability of users to perform work, it is worth examining the wheelchair to determine the work required. There are four factors which govern the work required to propel a wheelchair: the surface over which it is rolling, the slope, wind, and the rolling resistance of the wheelchair. Only the latter is a function of the wheelchair design, but the design can have an effect on performance with respect to the three environmental factors. For example, some tyres may be suitable for hard pavement but not for grass. Tyres are the single most important factor in determining rolling resistance on level terrain.

The total effort required to propel a wheelchair is the sum of the rolling resistance, the wind effect and the slope. On a firm level surface the rolling resistance may be as low as 6 newtons (N) or as high as 40 N, depending on tyres and alignment. The wind effect can be considerable. Coe (1979) at NASA Langley studied this in a low speed wind tunnel. With a drag coefficient considerably worse than a flat plate, a wheelchair will require a force of 12 N to overcome a head wind of 20 kmph. Doubling the wind speed would increase the drag force four times. The largest force to overcome is that due to gravity on ramps and hills. For a wheelchair and occupant weighing 100 kg the force required to mount a ramp of 1 in 12 gradient is

$$\frac{100}{12}\text{ kg or } \frac{100 \times g}{12}\text{ N}$$

$$= 82\text{ N}$$

where g = acceleration due to gravity

The total force required to move up the ramp must additionally overcome rolling resistance (say approximately 6 N) and wind resistance (typically 12 N).

$$\text{Total force} = (82 + 6 + 12)\text{ N}$$

$$= 100\text{ N}$$

The power required to generate this force depends upon speed. At 1 metre per second (m/s) this would be 100 W.

An average user with a maximum output of 30 W would be reduced to

$$1 \times \frac{30}{100} \text{ or } 0.3\text{ m/s (1 kmph)}$$

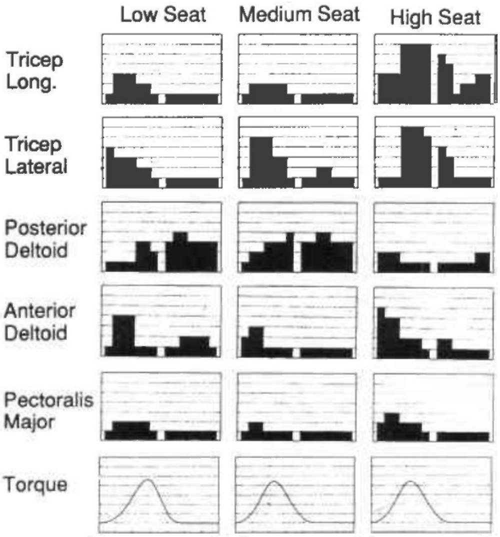

Fig. 7. Muscle activity of a person with normal arm function during a typical stroke cycle at three seat heights.

Wheels and tyres

The rolling resistance of tyres on a smooth firm surface has been measured at the UVA on a treadmill. For these tests, a special cart was constructed, to which a pair of wheels could be mounted. The cart was tethered to a force transducer to measure the pulling force with different loads and treadmill speeds (Fig. 8). From these tests it was concluded that the pulling force varied directly with the weight, but was nearly independent of speed. The tests also indicated a marked difference in the rolling resistance of different types of tyres. For example a high pressure pneumatic tyre required only one quarter of the pulling force of the solid grey rubber tyres which were in common use throughout the United States. The wheel

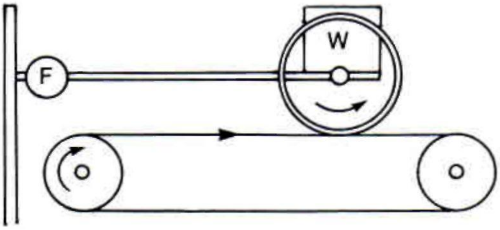

Fig. 8. Diagram of a test cart on a powered treadmill for measuring rolling resistance. The cart allows misalignment of the wheels to measure the effect of toe-in and toe-out.

alignment could also be adjusted on the cart. From this, it was learned that camber up to 10° (tilting the top of the wheels inward) has no significant effect on rolling resistance. Toe-in or toe-out, however, resulted in a serious increase in the pulling force. Only one or two degrees misalignment could double the required force (Fig. 9).

Studies regarding the rolling resistance of tyres on grass or other off-pavement surfaces are difficult to perform since there is no practical way to characterise or simulate such surfaces. However some indication may be inferred by test results on carpet. Ordinary tightly woven carpet can double the rolling resistance while shag carpet can cause an increase of five fold. On soft ground or sand, it can be assumed that wide tyres will roll more easily than narrow tyres. The diameter of the tyres also has a significant effect. As a general rule, the rolling resistance is inversely proportional to the diameter. Thus a castor wheel which is one third the diameter of a drive wheel, will have about three times the rolling resistance if it is carrying the same load. For this reason it is important to maintain as much weight as is practical and safe on the main wheels of a wheelchair.

Although pneumatic tyres are preferable to solid rubber from a standpoint of rolling resistance, comfort and weight, recent research has shown that this may change in the near future. Synthetic tyres are superior in wear resistance and not subject to flats from slow leakage or punctures. Kauzlarich et al. (1988) has been working on tyre design for some time and has concluded that a synthetic tyre can be designed to be much more durable, cheaper, lighter and with a rolling resistance comparable to pneumatics. Synthetic tyres are particularly advantageous for castor wheels where the small air volume causes difficulties in maintaining air pressure. Thacker et al. (1988) is currently examining ride quality of tyres with various spring suspension systems, so that even if synthetic tyres do not provide as smooth a ride, springs may more than compensate for this deficit.

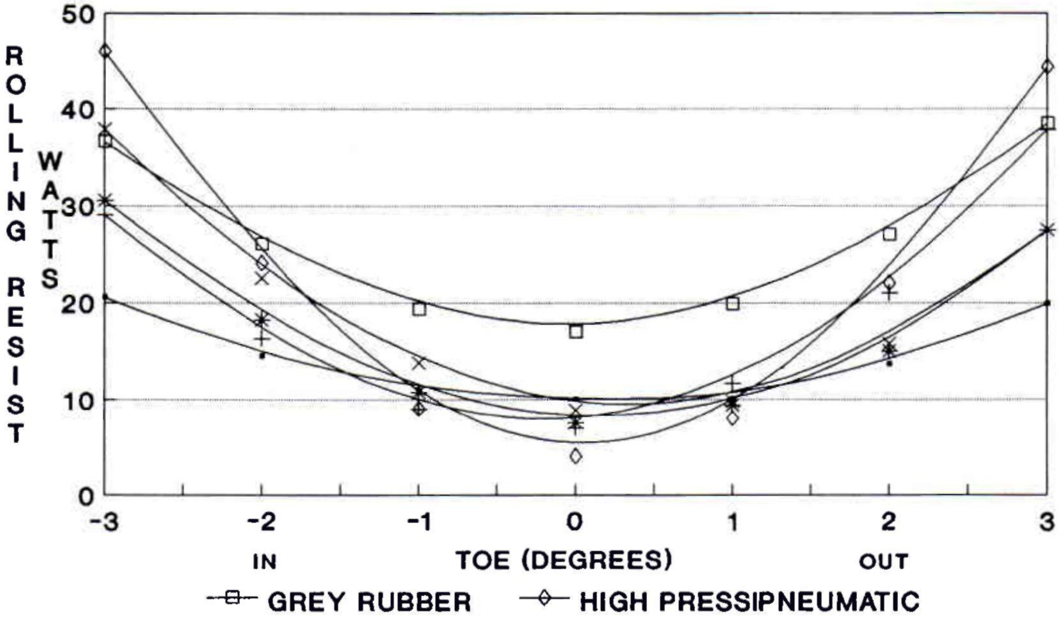

Fig. 9. Rolling resistance of several wheelchair tyres with changes in alignment. The rolling resistance is highly dependent on the type of tyre and the alignment. The tests were run at 4 kmph with a laden weight of 100.2 kg.

Tyres or springs which absorb shock also decrease the stress on the frame, axles and wheels. Two types of wheels are in common use, those with wire spokes and "mag" wheels where the rims, spokes and hubs are moulded or cast in one piece from lightweight metal or reinforced plastic. Using up-to-date bicycle technology, wire spoked wheels are the lightest available. Unlike the rear wheel of a bicycle, no torque is transmitted from the hub to the rim, unless hub brakes are installed. Thus straight radial spokes, instead of cross laced spokes may be used, resulting in a stiffer wheel. Also because a wheelchair wheel may experience heavy side loads when turning, the hubs may be wider to put the spokes at a more advantageous angle. In spite of being light but strong, wire spoked wheels are subject to damage, and once a few spokes are loosened, the wheel quickly deteriorates. For this reason the "mag" wheels are becoming more popular and in normal use should last indefinitely, requiring no maintenance. However, they are considerably heavier and usually more flexible. Common materials include aluminium, but most are made from nylon or similar plastic which has been reinforced with short fibres of glass or a similar material. Carbon fibre (graphite) is one of the strongest reinforcing materials and one wheel of Swedish design uses this in the tubular spokes to decrease the weight while maintaining strength. Recent innovations in bicycle technology suggest that composite construction may be used for disc wheels, utilizing a combination of reinforced plastic with a core component of foam or honeycomb.

No consideration of wheel design is complete without including the axle and bearings. Traditional ball bearings roll between cones, one outer and one inner screwed onto the axle. Although inexpensive, these bearings require frequent adjustment, which if not maintained can result in a loose wheel and damage to the bearings. Most modern wheelchairs use sealed ball bearings, which never require adjustment, and are sealed against the entry of dust and dirt. In normal use they should last the life of the wheelchair. Axles are a highly stressed part of a wheelchair, particularly when bouncing over kerbs. The strength is determined by the size, the material and the presence or absence of stress-raisers, such as threads at critical locations. Since the axle stress is not easily determined, the only safeguard for the buyer is the test results disclosed in Wheelchair Standard ISO 7176/8 strength tests, which applies to the wheelchair as a whole. Two types of axles are generally available, the fixed or bolt on type and the quick release type. The latter offers advantages in removal for stowage in a car, in changing to different wheels for off-pavement use or for changing to a different axle position.

Handrims

The material from which a handrim is made is an important factor. Farey's rims and those used for the testing at UVA were made of plywood which has a pleasant feel and appearance, but is much too expensive in production quantities. Also, it is generally believed that the rim should be metal to dissipate heat while braking, although no formal test results are available. Metal handrims may be aluminium, chrome plated steel, or stainless steel. The latter is to be preferred. Aluminium rims are easily scratched and dented, even when anodized. Without anodizing they leave black marks on the hands and clothing. Chrome plated steel rims are sturdy and have an excellent finish, but there is a danger that some of the plating may fail and start to peel off. This results in razor sharp bits of plating curling up off the surface which pose a severe threat to any skin that comes into contact. NASA (Fig. 10) has produced composite handrims for experimental purposes. These are light and strong, with a smooth surface, and can be produced in any colour. Vinyl and other plastics are used as a coating over metal rims to increase friction. These too, can be produced in any desired colour. Softer foam covers have also been introduced, to increase gripping friction and to avoid injury to insensitive hands. Although these have not been

Fig. 10. An experimental wheelchair with the seat, side panels and hand rims produced by NASA. The panels have a foam core with skins of Kevlar and graphite impregnated with epoxy resin.

used extensively, the approach has considerable merit when compared with the pegs and knobs that are often used to aid propulsion for persons with quadriplegia.

Castors

Although some wheelchairs, particularly outdoor lever drive models and racing wheelchairs have steerable wheels, most wheelchairs use castors because they allow motion in any direction. The basic castor consists of a wheel, an axle, a fork and a stem. Wheels are available in several sizes. A smaller wheel (5in or 125mm in diameter) may be quite satisfactory for indoor use, except on thick carpet. For outside use, even on pavement, the small castor produces a jolting ride and is easily caught up on bumps and holes. Even larger wheels (8in, 200mm) can fall into cracks such as those found on elevators and for this reason and others, wide tyres are preferred over narrow ones. Pneumatic tyres, although they roll easily and provide cushioning are difficult to keep inflated. To ensure easy rolling, the wheel and axle must have ball or roller bearings. Since the axle is close to the ground, bearing seals are needed to exclude water and dirt.

The fork is one part of the wheelchair that is easily damaged, particularly where it attaches to the stem. Damage occurs from impact with obstacles such as kerbs and pot-holes. The frame adjacent to the castor is also one of the highly stressed points. The castor stem is one of the most critical parts of a wheelchair. If the stem is not vertical, but is tipped to the left, then the wheelchair will turn to the left when coasting. This is the primary reason for poor tracking characteristics. Also if the stem is tipped forward at the top, the effective trail is reduced. The trail is the distance from the ground contact of the tyre to the spot where the axis of the stem would intersect the ground. With a vertical stem, this dimension is the distance of the axle behind the stem (Fig. 11). The trail is an important parameter. A long trail makes turning easier but causes the castor wheel to sweep through a greater arc, taking up more room in the area of the footrests. A long trail also means that castor flutter is less likely to occur. Castor flutter or shimmy is not only annoying and energy consuming, but can be very dangerous. The rolling resistance of a castor can multiply ten times or more when fluttering. Thus, when coasting down a gradient, the onset of flutter acts like a brake which can, and often does, cause the occupant to be thrown forward out of the wheelchair.

In addition to the trail, castor flutter is influenced by the weight of the tyre. A large heavy tyre is more prone to flutter than a light one, and can be much more troublesome when it does. However a tyre with a wide tread or a dual tread can help to damp flutter, or increase the speed at which flutter will occur. Damping can also be produced by mechanical friction or hydraulic action at the stem. The latter has the advantage of incurring little resistance at low rotation speeds, with high resistance at high rotation speed of the castor at the stem. At this time, however, no hydraulic units are available commercially for this purpose. Several mechanical friction devices have been demonstrated and some manufacturers will supply them. One design developed at UVA consists of a pair of nesting cones surrounding the castor stem inside the castor housing. A compression spring forces them together, causing friction on the stem which effectively prevents flutter for normal wheelchair speeds. It has been tested for a million cycles without appreciable wear. The device does result in increased turning force, but this is small compared to that induced by friction of the tyre.

The Frame

Although some generalization can be made regarding the materials and construction of the frame, the overall design should depend upon the characteristics of the user. A simple lightweight frame may be ideal for an athletic active user, but be quite unsuitable for someone requiring a

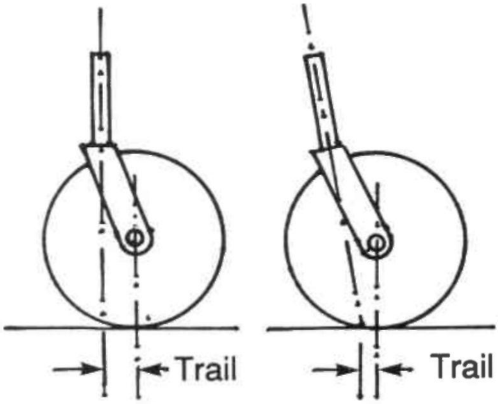

Fig. 11. Diagram of a castor illustrating how the trail is reduced if the stem is tipped off the vertical. This increases the incidence of castor flutter or shimmy.

reclining back support or elevating leg supports and who usually travels with a carer or companion. The simple lightweight frame, which has become popular in recent years, may be either folding or non-folding. The non-folding style has advantages in saving weight while maintaining durability. With quick release axles, stowing in an automobile is possible, particularly if the back is low or folding. For most purposes a folding frame is desired, not only for vehicular travel, but for space saving within a home. Most wheelchairs use the "X" frame or "camp stool" type of folding mechanism. One of the problems with this mechanism is that the frame alignment and hence the wheel alignment can change with persons of different weight, causing increased rolling resistance. Flexibility is often built into the frames to allow all four wheels to contact the ground in spite of irregularities. Apart from alignment problems, many users prefer the feel of a rigid frame and some folding models are designed with this in mind. Frames that must support elevating legrests and reclining backrests will be considerably heavier than the simpler styles. In these models, the ease and security of the adjustments should be checked, but of prime importance is the geometry of the mechanism. Since the hinges for the back or legrests do not correspond with the human hip and knee joints, the wheelchair may not fit the occupant correctly when leg or back adjustments are made. This should be checked before prescription. The back is particularly critical since lowering the back with the occupant seated can cause shear forces between the person and the chair.

The common frame material for wheelchairs is mild steel tubing. It is both inexpensive and durable, but can be heavy. In order to save weight many manufacturers have been offering other materials, such as alloy steels and aluminium alloys which can reduce the weight by half with comparable strength, but perhaps double the cost. Aluminium alloy frames even with an anodized finish are easily scratched and soon lose their pristine appearance. Steel frames may be chrome plated, which provides a durable easy to clean finish, or painted. Paint which can be applied to aluminium or steel is also easily scratched, although the choice of colours has an appeal to many users. Stainless steel, although expensive, offers a most durable finish although weight saving compared with mild steel is minimal. Recently plastic frames have appeared on the marketplace. These have advantages with colour that is integral with the material, and since no finishing is required, cost savings can be realized. Even though the plastics include reinforcing fibres, the result is a more flexible frame than those made from steel. Also some designs include a myriad of webs and stiffeners between which dirt can collect. Frames made from reinforced plastic tubing have also been used. These are strong and light but joining the tubes has been a problem. As in the automobile industry, the use of plastics in wheelchairs is likely to increase but to use plastic effectively in frames, conventional design must be abandoned. As new designs suitable for plastics emerge we can expect to see the benefits of low cost, colourful and functional frames from plastic and composite materials.

Seating

Seating in a wheelchair for comfort, postural control and skin care is a separate topic. In this paper only two aspects will be discussed, adjustments and material properties of the seat and backrest.

For many years, the common material for both seat and backrest has been reinforced vinyl fabric. It is moisture proof, abrasion resistant and easily cleaned. It also exhibits undesirable properties such as stretching. The moisture-proof nature of the material prevents it from "breathing" and hence it is hot and uncomfortable in warm weather. This drawback is less important in the seat where a cushion may be used, but here the stretching quality causes the seat to sag, altering the support characteristics and creating excessive pressure under the trochanters.

Fortunately many models are now available with sturdy fabrics woven from synthetic fibres such as "Cordura", a material used in back-packs and similar applications. These fabrics can be fitted much more tightly than vinyls, resulting in a flatter seat. Because of the benefits of a flat seat that does not stretch, there is a current trend towards solid seats. With good design and appropriate materials, a solid seat adds little in weight, increases structural integrity, allows folding and should never need replacing. Solid seats have been made from plywood, which tends to be heavy, from reinforced plastics, and from composites, such as panels with skins of epoxy impregnated graphite and/or Kevlar bonded to a core of foam or honeycomb (Fig. 10).

Seating adjustments are becoming more common in wheelchair design, but it should be remembered that any adjustment carries a penalty in cost, weight and strength. Common adjustments are seatback angle and seatback height. Seat angle and seat height adjustments are also available, but perhaps the most important adjustment is to allow the centre of gravity of the user to be positioned correctly with respect to the main wheels. This is commonly done by providing a selection of axle positions. This not only changes the wheelbase, possibly resulting in castor interference, but may change the axis of the castor stem, requiring an adjustment in that mounting bracket. These problems can be avoided if the seat can move with respect to the sub-frame or chassis. Some experimental models have been built that allow the user to adjust the seat forward and backward while seated. This can be especially useful while ascending slopes, where the weight should be forward to prevent backward tipping.

Footrests

From the designer's viewpoint, footrests are a very difficult challenge. They may be subject to high loads from a user in extensor spasm, and from inadvertent impact with kerbs, doorways and other obstacles. They should be independently adjustable and easily removed for easy transfer in and out of the wheelchair. For a tall person, seated at a normal height, they must be positioned well forward to keep the feet above the floor and to avoid interference with the castors. If leg elevation is required, the problems are further increased.

Many lightweight sport type wheelchairs have used a bar or pair of bars joining the two sides of the frame in front of the castors. This is light and strong, but does not allow individual adjustment and removal for transfer. The most popular means for removal is the swing away type which can also be lifted off when the lock is released. The foot plate may be cast aluminium, reinforced plastic or tubular construction, the latter being light and strong, but providing less support for the foot. The foot plate is usually hinged to fold upwards, adding a little more weight and complexity. The foot plate is usually attached to the supporting tube by a friction clamp. This can be advantageous during impact, allowing the structure to slip rather than break.

Individually adjustable, and contemporary swing-away footrests require that the feet be placed some distance apart, depending on the width of the wheelchair and the size of the foot plates. For many persons it is more desirable to place the feet together. Apart from postural and aesthetic reasons, this tends to avoid spacial interference with the castors. This foot position presents no problem with one piece footrests, but requires clever geometry in the structure and hinging of individually adjustable models, something which has yet to appear on the market. As a general rule, the selection of an appropriate footrest should be based on the *simplest* design that can accommodate the needs of the user.

Armrests

Much of the discussion on footrests applies to armrests. Fixed armrests, as an integral part of the frame are the lightest and strongest solution but provide no adjustment and may interfere with transfer. The ISO Wheelchair Standards state that an armrest must be strong enough and secure enough to allow lifting of the wheelchair and occupant *or* release before lifting so that there is no danger of releasing during the lift. Traditional removable armrests which plug into vertical sockets must therefore have very secure latches or none at all. Many wheelchairs now have armrests of a different design, the most common being one that is pivoted at the rear so that it swings upwards and backwards to avoid interference when transferring. This type of armrest avoids the lifting problem and avoids the inconvenience of a separate part which can be dropped or misplaced. A possible disadvantage is the absence of a skirt to prevent clothing from contacting the wheel. The common adjustment to armrests is for height which may not yet be available in the pivoting type. The type of armrest may also be dictated by the need for a lap tray which is usually fastened to the armrests.

Brakes

Most manual wheelchairs are equipped with brakes for parking. Braking to a stop or while descending a slope is accomplished by friction to the handrim. Some wheelchairs are equipped with dynamic brakes that can be used for both functions. These are of special value to those with impaired hand function or where hills are frequently encountered. Using the hands for braking on a hill can cause skin damage and is inadvisable for those with insensitive skin. Most persons with quadriplegia have little or no ability

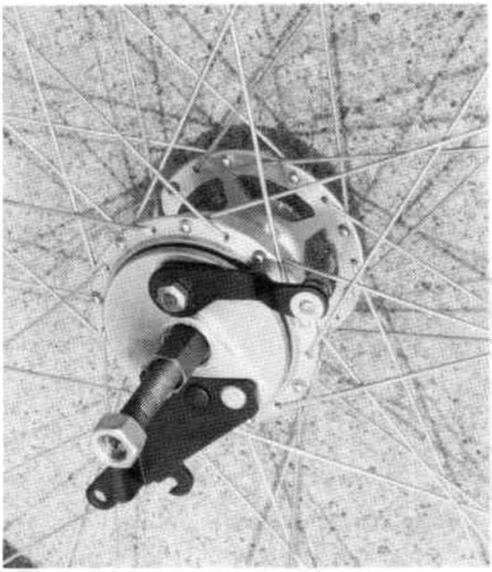

Fig. 12. A drum type dynamic brake for use on a wheelchair. Note that, as in a bicycle the spokes must be cross laced.

to descend slopes safely unless the wheelchair is equipped with dynamic brakes. A survey conducted by UVA and the Paralyzed Veterans of America indicated that most users wanted such brakes, but they are not yet available in the United States.

Dynamic brakes are available in Europe in two different types, one which operates on the tyre, and one which operates on the wheel hub. The latter is preferable since it will work with a flat or worn tyre, but it does carry a penalty in weight and cost. Hub brakes (Fig. 12) are usually drum type adapted from bicycle technology. Disc type brakes at the hub or calipers acting on the rim have also been used. Studies at UVA have shown that the calipers do not provide as smooth control as the drum type and may be affected by rain. The effectiveness and the operating force for wheel locks is included in Wheelchair Standard ISO 7176/3.

Chassis configuration

Although a wheelchair can be considered to be the sum of its parts, the way in which these parts are assembled can profoundly affect the performance of the wheelchair. Wheelchairs with rear castors and large front wheels may be easier to propel for some persons, and be easier to manoeuvre in a restricted space. Rear castored vehicles, including wheelchairs, are directionally unstable. When coasting, any slight force or obstacle that tends to change the direction of motion will automatically result in a violent swerve. This is easily demonstrated by pushing and releasing the wheelchair, empty or loaded. A front castored vehicle is directionally stable, and will quickly recover from any force or obstacle that tends to divert it from a straight path. Either model may have misalignment of the castor stem or other imperfections that cause tracking irregularities, but the basic principle of castor position and stability is universally applicable. The reason lies not in the castors themselves but in the position of the centre of gravity with respect to the wheels with fixed axles (in this instance with the main wheels). If the mass is behind the main wheels, then if these wheels are caused to turn a little from the direction of motion, they are pushed further into the turn by the inertia of the mass. A mass in front of the main wheels (i.e. front castors) will tend to pull the wheels out of the turns. Some wheelchairs have been built with the centre of gravity located directly over the main wheels, with one castor in front and one behind. Such wheelchairs have neutral stability with no tendency towards stable or unstable direction (Fig. 13).

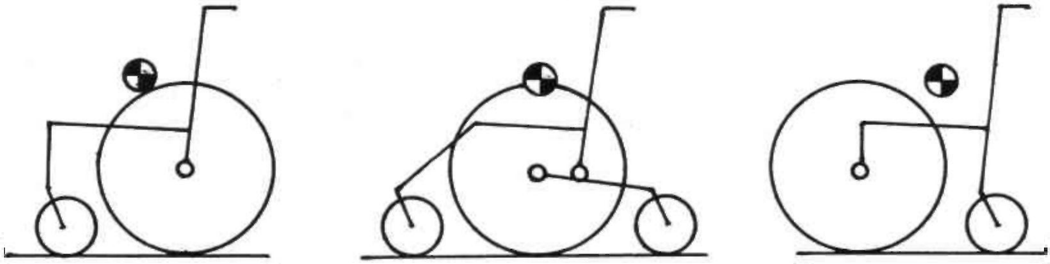

Fig. 13. The directional stability of a wheelchair depends upon the position of the centre of gravity with respect to the main wheels.

Directional stability is not important at low speeds, except when traversing a side slope. Most outside paved surfaces have side slopes for drainage. A front castored wheelchair will tend to turn downhill on a side slope. A rear castored wheelchair tends to turn uphill and a wheelchair with the weight directly over the main wheels will tend to go straight. This tendency to turn on a side slope depends upon the distance of the centre of gravity in front of or behind the axis of the main wheels and the angle of the slope. The turning moment is the product of the distance of the centre of gravity from the axis of the main wheels and the component of gravity that is parallel to the slope (Fig. 14). This turning moment must be countered by increased effort on one handrim and decreased effort or braking on the other handrim. The net result is an increased energy requirement which depends upon the width the wheels are apart as well as the previously mentioned factors. A side slope of as little as 2° may require double the energy for propulsion. Ergonomic testing however, has shown that the metabolic energy may not be doubled since one arm is doing the work, and for low energy levels, one arm is more efficient than two, since it is working more closely to optimum conditions.

A centre of gravity close to the main wheels may be an advantage in other situations, and may actually be safer. It has been shown that rolling resistance is decreased as more weight is transferred to the main wheels. Taking weight off

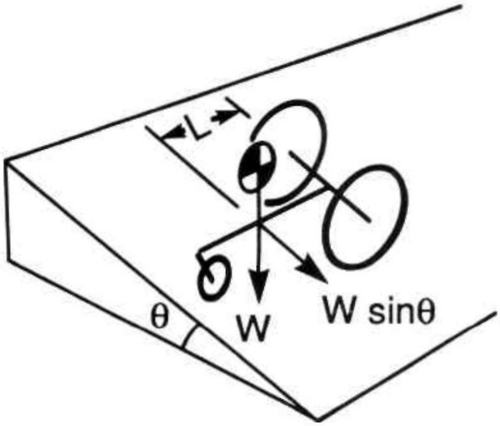

Fig. 14. A diagram showing the forces acting on a wheelchair traversing a side slope. With a front castored wheelchair the downhill turning moment is the product of the distance of the centre of gravity forward of the main wheels and the total weight multiplied by the sine of the angle of slope.

the castor wheels also reduces the turning force at low speeds and makes "wheelies" (balancing on rear wheels) easier and safer. Wheelies are useful on rough terrain, are essential for mounting kerbs, and are a useful postural variation. They are accomplished by a combination of backward leaning while accelerating forward with the handrims. With a centre of gravity slightly forward from the main wheels, the mass rises only very slightly and little effort is required. With the centre of gravity far forward of the main wheels the tilt angle is great and the mass rises considerably, and a strong effort is needed to accomplish the task. Too much effort can result in tipping over completely.

Anti-tipping bars (wheelie bars) are a common accessory but are seldom used. They are an obvious safety device if one is to practise wheelies, but unless properly positioned they can be a nuisance. For example, if they are positioned to allow tipping with the castors high enough to clear a kerb, they will catch on the kerb when dropping off the kerb in the wheelie position.

Wheelchair Selection

It is true that some wheelchairs are better built than others, have a better finish, are aesthetically more pleasing or perhaps are more fashionable. For structural integrity the purchaser can review the ISO test results which should be disclosed by the manufacturer (ISO 7176/8). This also applies to other ISO standards covering static stability, (7176/1) efficiency of brakes (7176/3) overall dimension, mass and turning space (7176/5) and seating dimensions (7176/7). It is hoped that this article by providing general information regarding specific details of construction, materials and configuration will be of assistance when choosing a wheelchair with the best characteristics for a particular person and unexpected usage. Unfortunately, a checklist, matching personal requirements with functional features becomes rather confusing. For example a light, elderly person may need a lightweight wheelchair, but with the reliability of solid tyres and the extra weight of elevating legrests. It is suggested that, when choosing a wheelchair, the characteristics and needs of the user be listed and matched as closely as possible, feature by feature with available models, considering the options and accessories.

Particular mention should be made concerning weight, since this is one of the most popular

Table 3. Component weight comparisons for two wheelchairs

Component	Weight in kg (lb)	
	Conventional	Sports
Frame	6.7 (14.7)	3.8 (8.3)
Seat	1.0 (2.1)	0.3 (0.6)
Back	1.0 (2.2)	0.3 (0.6)
Armrests	1.9 (4.2)	–
Footrests	2.7 (5.9)	0.8 (1.8)
Wheels, Tyres, Rims	5.1 (11.2)	3.8 (8.3)
Axles & Hardware	0.4 (0.9)	1.1 (2.5)
Castors	2.0 (4.5)	1.8 (4.0)
Wheel Locks	0.5 (1.2)	0.5 (1.0)
Total	21.3 (46.9)	12.4 (27.1)

features of newer models. Certainly there is little place for the 25 to 30 kg models that were common a few years ago when similar durability is now available for 15 to 20 kg. However it should be remembered that the total weight may be quite different from the stripped down weight. Each time a new accessory or different feature is added, the total weight may be increased (Table 3). For steady-going on level ground weight may not make much difference. The type of tyre and wheel alignment is more important. When going uphill, weight can make a significant difference, but since the occupant may weigh three or four times as much as the wheelchair, an increase of 10% in the wheelchair weight will result in only about a 3% increase in the propulsion effort. Weight plays a very significant role, however, when the wheelchair must be lifted for stowage in an automobile, or hauled up a flight of steps even when empty.

Finally, after many years of conservancy the wheelchair industry is responding with an impressive variety of design alternatives and innovations. The effectiveness of these in helping the people that use them will depend on how wisely the choice is made.

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