Future Developments

Current Directions in Wheelchair Research

by Colin A. McLaurin, ScD

Prior to his retirement, Dr. McLaurin was Project Director and Research Professor of Orthopedics and Rehabilitation at the Rehabilitation Engineering Center, Department of Orthopedics and Rehabilitation, University of Virginia Medical Center, Charlottesville, VA.

INTRODUCTION

Over the past several years, there has been increasing interest in the wheelchair among inventors, design engineers, and the general public. This is probably because the wheelchair has come to symbolize the person with handicaps. For example, the national symbol for handicapped access is an abstract image of a person in a wheelchair. It is a tangible and understandable object, and in recent years has become the focus of a great many ideas and suggestions for improvement.

In contrast, the major manufacturers of wheelchairs have been rather conservative in introducing new ideas and have instead been content with minor product improvements, particularly with regard to powered wheelchairs. The exception has been the production of the sports-type wheelchair, which was first conceived and developed in response to competitions in racing, basketball, and other sports for athletes with disabilities. Sports-type wheelchairs for general use were first introduced by new companies such as Quadra and Motion Designs, but are now offered by all major manufacturers. The revolution in lightweight wheelchair design and styling is a credit to the spirit and vitality of the people behind this movement, many of whom have disabilities.

However, problems of liability and the rather low overall market demand has contributed to a conservative attitude among manufacturers. Although the amount of research done by wheelchair manufacturers is not public information, it is doubtful that much effort is being devoted to this area by them. Some universities are appropriately staffed and equipped to carry out research on wheelchairs, paving the way for greater innovations in component design.

For example, a major research effort at the University of Virginia Rehabilitation Engineering Center has focused on the basic principles associated with the functional and structural characteristics of wheelchairs. These include ergonomics of propulsion, rolling resistance, seating configuration, structural analysis, controller design, motor efficiency, and battery capacity. Research efforts, such as those at UVA, are providing the theoretical framework which will result in designs that will meet the needs of disabled users for specific activities.

The definition of the user population and their activities, both customary and desired, needs to be known. To date, there has been very little research in this area, but some information can be obtained from surveys conducted by the University of Virginia (1) and the Paralyzed Veterans of America (2).

FUNCTIONAL CHARACTERISTICS

The primary purpose behind research is to improve the functional characteristics of a wheel-

Table 1.
Distribution of Subjects in Anthropometric Survey, 52 Clients

Diagnosis	Number of Clients		Range of Age	Mean Body Weight
	Male	Female	Years	Kg.
Cerebral Palsy	7	11	2-22	58.1 ± 29.9
Muscular Dystrophy	3	2	10-54	88.1 ± 45.3
Spina Bifida	3	3	15-20	104.2 ± 17.4
Paraplegia	9	1	19-53	165.0 ± 46.2
Quadriplegia	4	3	20-45	143.1 ± 37.1
Arthritis	2	2	64-79	142.9 ± 38.7
Other	0	2	28-50	104.0

chair. These can be divided into two categories: 1) seating comfort, and 2) mobility.

Seating Comfort and Support

Much has been said about the inadequacies of the sling seat, but very little has been documented to support this opinion. However, it requires little observation to note that just minor differences in wheelchair seating, usually only width and depth, can hardly accommodate the range of sizes, disability types, personal attributes, and activities that exist in the user population. It is the first duty of researchers to establish information regarding these individual requirements, and such work is underway. This topic is discussed in more detail by Ferguson-Pell elsewhere in this publication.

Perhaps the most basic work is the collection of anthropometric data for wheelchair users. The RECs at Memphis and Virginia have been collecting such data for several years now, and hopefully more centers will contribute to this compilation (3). Information completed from 52 subjects for 7 disability groups is shown in **Tables 1 and 2** (4). A report of anthropometry for cerebral palsy (5) compiled by the Memphis REC includes nineteen seated dimensions for ages 2 to 55 years. Relaxation and functional activities for persons with cerebral palsy also have been studied at Memphis to determine the most appropriate seating angle, and these studies will be expanded to include other disabilities.

In addition to the anthropometric data, more needs to be known about the ideal shapes for support surfaces for various parts of the body. For this purpose, a shape-sensing device has been developed and is in use at UVA. Probes projecting through a cushion in the seat and back of an adjustable chair automatically record the shape in a computer. By using cushions of different density, the tissue characteristics can also be deduced. Corresponding pressure readings and related work with magnetic resonance imaging (MRI) are providing the necessary information for determining the ideal shapes and cushion characteristics for seats and other support surfaces. This shape measurement technique is now used to produce numerical data for the automatic shaping of custom contoured cushions that are currently under evaluation. Since seating requirements may vary with activities, some form of adjustment while seated (like those done for automobiles) may be indicated.

Mobility

To a considerable extent, mobility is dependent upon seating, as it is one of the ergonomic factors. (Ergonomic factors are more fully described by Brubaker elsewhere in this publication.) Mobility also depends upon the rolling characteristics of the wheelchair.

One of the most important factors contributing to propulsion efficiency is mechanical advantage, since it determines if muscles perform at optimum speed and force. Experimental models have been built with a geared transmission in the hub, allowing two or more ratios between the handrim and the drive wheel. Lever or crank drives, or handrim drives that are separate from the drive wheels, provide a simpler means for obtaining an optimum mechanical advantage through a bicycle-type chain and sprocket transmission (**Figures 1a and 1b**). Since levers have been shown to be more efficient than handrims, their use in wheelchairs can be expected to increase in the future. The main disadvantage of levers—the difficulty in achieving the control and maneuverability associated with handrims—appears to have been overcome by recent designs. In any event, the lessons learned by studying propulsion with handrims, levers, or other means will have significant impact on the future design of wheelchairs.

Equally important are the rolling characteristics of the wheelchair itself. At one time, hard rubber tires were prescribed for low resistance, but studies

Table 2.
Statistical Analysis of Anthropometric Survey, 50 Clients

	Dimensions in Centimeters											
	Cerebral Palsy		Muscular Dystrophy		Spina Bifida		Paraplegia		Quadriplegia		Arthritis	
Linear Measurements	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1. Sitting Height	63.5	± 9.9	68.7	±12.0	68.9	±6.0	84.0	± 6.0	89.9	± 9.0	77.7	± 6.2
2. Shoulder Height	40.6	± 6.7	46.5	± 8.7	45.9	±4.9	56.7	± 5.0	61.9	± 8.4	53.2	± 4.2
3. Elbow Height	17.7	± 5.1	17.3	± 7.6	17.0	±4.8	19.1	± 4.8	25.5	± 7.4	20.0	± 4.9
4. Elbow to Knuckle of Small Finger	26.6	± 6.1	31.0	± 3.9	31.3	±2.2	36.9	± 1.8	41.1	±14.0	31.9	± 3.3
5. Back to the Kneecap	44.1	±11.3	52.1	±10.8	49.0	±2.5	58.8	± 4.5	59.7	± 2.7	59.1	± 3.6
6. Back to Underside of Knee	37.6	± 9.6	45.8	± 9.6	42.1	±1.8	50.3	± 4.3	51.5	± 4.0	50.7	± 3.8
7. Ground to Underside of Knee	58.7	± 5.8	63.6	± 9.0	54.1	±2.0	54.6	± 3.9	53.1	± 3.5	50.5	±10.4
8. Ground to top of Knee	66.6	± 6.2	72.4	± 8.3	63.0	±2.3	65.2	± 4.8	63.9	± 4.0	62.4	±13.7
9. Ground to heel	26.9	±11.2	27.4	±15.1	28.0	±7.2	7.1	± 4.0	12.2	± 9.4	11.9	± 7.7
10. Shoulder Width	31.2	± 6.9	35.5	±10.4	42.6	±7.2	44.2	± 3.2	44.0	± 7.4	37.6	± 4.8
11. Chest Width at Axilla	23.5	± 4.3	26.0	± 8.7	32.0	±4.6	35.2	± 4.0	34.5	± 5.1	29.9	± 2.9
12. Waist Width	20.0	± 3.6	26.7	± 4.8	30.1	±7.0	32.5	± 5.6	30.6	± 6.6	32.7	± 6.0
13. Hip Width	24.8	± 5.7	32.6	±10.7	37.2	±6.0	41.1	± 6.7	40.3	± 4.8	41.8	± 4.1
14. Width at Knees	26.4	± 5.9	25.2	±11.6	31.1	±7.2	31.2	±10.4	26.0	± 6.8		
15. Foot Length	18.7	± 4.4	22.9	± 1.6	18.8	±2.0	26.3	± 2.9	26.5	± 1.6	25.4	± 4.0
16. Leg Length	33.3	± 7.9	39.8	± 7.7	34.3	±1.8	51.4	± 7.1	47.4	± 3.9	45.4	± 6.8
17. Acromian Width	24.1	± 4.4	35.6	± 4.5	34.4	±4.0	39.5	± 4.4	39.2	± 3.3	34.8	± 3.8
Angular Measurements	Angles in Degrees											
< 6 - Angle of Seat Surface to Horizontal	18.5°	±13.4°	8.3°	± 9.9°	2.7°	± 3.8°	2.5°	± 1.6°	2.1°	± 2.4°	6.5°	± 7.9°
< 1 - Angle of Back Surface to Horizontal	110.7°	±16.9°	109.3°	±12.6°	96.2°	± 6.4°	103.7°	± 4.9°	106.6°	± 7.2°	103.0°	±12.9°
<16 - Angle of Post. Leg Sur. to Horizontal	107.8°	±11.8°	105.8°	± 3.0°	124.7°	± 9.6°	106.°	± 3.5°	114.°	±12.5°	107.°	±12.7°
<15 - Angle of Foot to Horizontal	15.6°	± 8.5°	14.0°	± 6.6°	6.2°	±11.7°	14.9°	± 6.6°	17.0°	±15.5°	22.5°	±18.4°
< 4 - Angle of Forearm to the Horizontal	11.2°	±16.8°	76.0°	±50.5°	2.3°	± 5.7°	−4.3°	±12.5°	6.6°	±11.7°		

on a treadmill have shown that it may require about four times the effort to propel hard rubber tires than that required for high pressure pneumatic tires. Some synthetic, non-inflatable tires show results nearly as good as high pressure pneumatic tires but with limitations in comfort. This may indicate the need for some type of suspension which could provide comfort as well as the durability associated with the new synthetic materials. Theories have been put forward by Kauzlarich regarding the optimum design of such tires for easy rolling (6). Since smaller wheels such as those used in casters have a rolling resistance greater than large wheels (roughly inverse to the size) the weight of the user and wheelchair should be kept over the large wheels. This also provides better balance for performing wheelies and other maneuvers.

Other factors that affect rolling resistance are alignment and caster flutter. One degree of misalignment can double the rolling resistance. (However, camber—the tipping inward of wheels at the top—has little or no effect.) Frames must be made that maintain correct alignment under any load. Caster flutter, a long standing and widely experienced problem, has now been thoroughly analyzed and there is no longer any excuse for this annoying and dangerous problem (7). One device recently developed, that weighs less than an ounce, effectively dampens any flutter for speeds up to 12 kph and beyond. The design utilizes cone shape wedges and a compression spring mounted in the caster housing (**Figure 2**). The spring forces the cones against the caster stem, effectively damping flutter for all reasonable speeds.

With the advent of sealed bearings, only the tires, irregular surfaces such as carpets and hills, or the wind will limit progress. It has been shown that carpets increase resistance by as much as four times with typical tires, but little is known about tire design for use specifically on carpets, grass, or similar surfaces. The biggest energy consumers for the wheelchair user are hills, but other than reducing the weight little can be done without resorting to innovative propulsion systems. A lever drive with variable gear ratios and an anti-back up device is an example. Wind resistance has been measured in a NASA low speed tunnel, indicating that a head wind of 20 mph can increase the drag force on level terrain from 1.5 to 9 pounds (8). This information could be used in designing a propulsion system optimized for all conditions.

Figure 1a.
Lever Drive Wheelchair in Operation. In this prototype, the rear wheels are driven by the lever through a clutch and bicycle chain. The clutch is engaged by moving the levers inboard, allowing the wheelchair to be driven forward or backward by a similar motion in the lever. Propelling the wheelchair is like rowing a boat. The clutch is released at the end of each stroke by outboard motion of the lever, similar to lifting the oars from the water. The clutch also acts as a very effective dynamic brake and the chain drive allows the selection of a speed ratio suitable for the strength of the user.

To summarize, theoretically it is possible to increase the power available in the arms and shoulders by a factor of three, over that available in a conventional wheelchair. It is also possible to decrease by a similar amount the power required to move the wheelchair. This has already been achieved, in part, by the introduction of sports-type wheelchairs for everyday use. Research results are providing the necessary information for designing a machine with optimum features for a given person and intended activities.

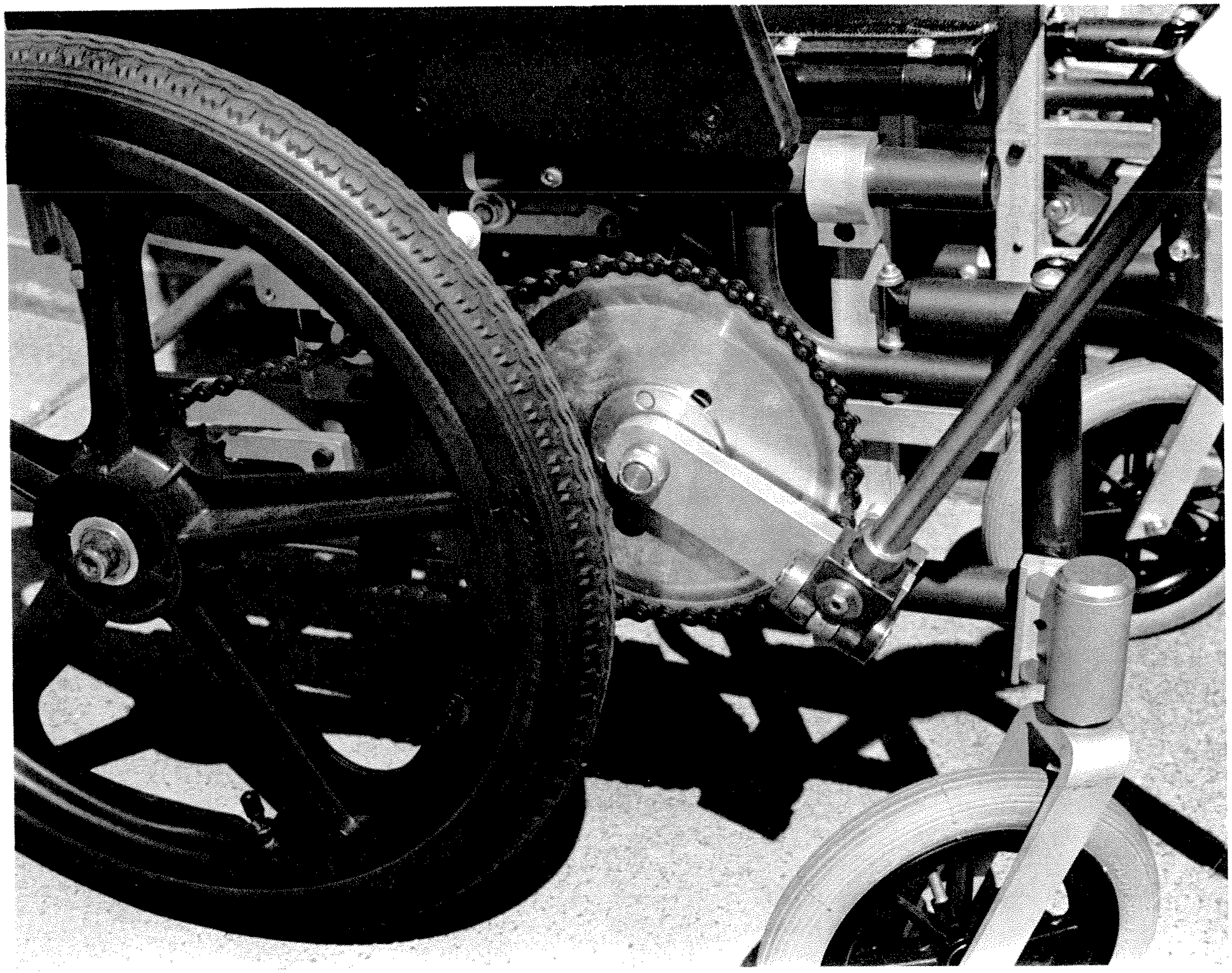

Figure 1b.
Lever Drive Wheelchair in Operation. Detail of the clutch assembly. The front sprockets serve as the clutch plate in a recent prototype of the lever drive system. The system has been designed to be retrofitted to commercial wheelchairs.

MANUAL WHEELCHAIRS: THE EFFECT OF RESEARCH ON COMPONENT DESIGN

Much like bicycles, wheelchairs are an assembly of components with varying and optional characteristics that include a frame, seat, foot and armrests, wheels, tires, brakes, and drive systems.

Frame

Tubular construction will probably be the mainstay for some time to come. Material options such as aluminum alloys, titanium, and carbon fibers all have their own characteristics. No matter what material is used, stress analysis systems, some simple enough to conduct on a personal computer, are now available that allow designers to ensure adequate strength where needed. An example is the tube adjacent to the caster, which has been shown in analysis and testing to be a highly stressed point. By simply replacing the round tubing with square tubing at this point, the strength is increased by about 38 percent.

Plastics are being used more and more in frame design. Reinforced plastics such as carbon-epoxy tubes, or composites that can include panels with foam or honeycomb cores, are light and strong. Production cost estimates show that side frames can be produced in quantity for as little as $15, because

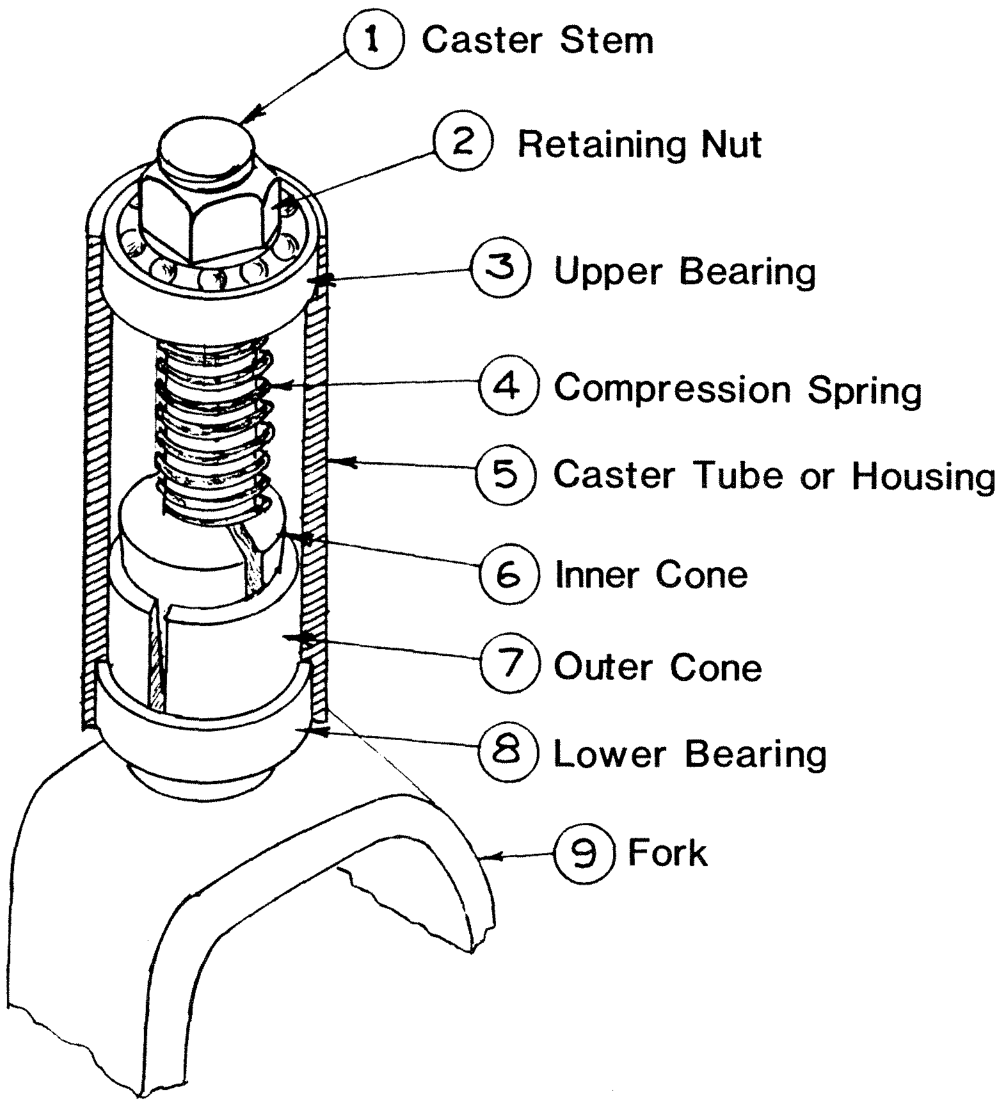

Figure 2.
University of Virginia Shimmy Damper. The cutaway drawing shows the three components of the friction type damper in a typical installation. The spring (4) forces the inner cone (6) into the outer cone (7). This causes the inner cone to press against the caster stem (1), thus producing friction to damp rotational oscillation. Both the inner and outer cones are split so that they are free to move radially. Parts (1) caster stem, (2) retaining nut, (3) upper bearing, (5) caster tube or housing, (8) lower bearing, and (9) fork are existing parts of a typical wheelchair.

these parts are made in a one-step process requiring no further finishing.

Frames should adjust to suit the individual. Experimental plastic models have shown how the front and back position over the wheels, the seat angle, and the seatback angle can be adjusted with simple tools and with little weight penalty. These adjustments should become a part of routine wheelchair prescription. Ideally, it should be possible for the user to make adjustments such as front and back positions without leaving the seat, as has been demonstrated in experimental models.

Seats

For simplicity, sling seats will probably continue to be used routinely. But the variety of plastic and composite panels being developed suggest that more consideration be given to rigid seats which provide firm and predictable support for the seat cushion, a prerequisite for so many users. In the past, rigid seats have been flat, but the use of contoured shapes opens up new possibilities for comfort and support, with or without a cushion. Current research is determining the required shapes and sizes for such seat panels.

Lightweight Frame with Adjustable Seat Systems

No wheelchairs are commercially available that reflect the design and development of seats having the optimum support characteristics determined by research, plus the light weight and foldability required for wheelchair use. This is a considerable task, if one is to remain within the fiscal restraints of the market. A prototype developed by the author is shown in **Figures 3a and 3b**.

Footrests and Armrests

Previously, footrests were one of the most cumbersome and vulnerable parts of a wheelchair. With the development of sports wheelchairs, new approaches to designing footrests were introduced. Combining the support required in prescription wheelchairs with swing-away footrest features and simplicity in design of sports chairs, calls for more ingenuity than research. But the current enthusiasm

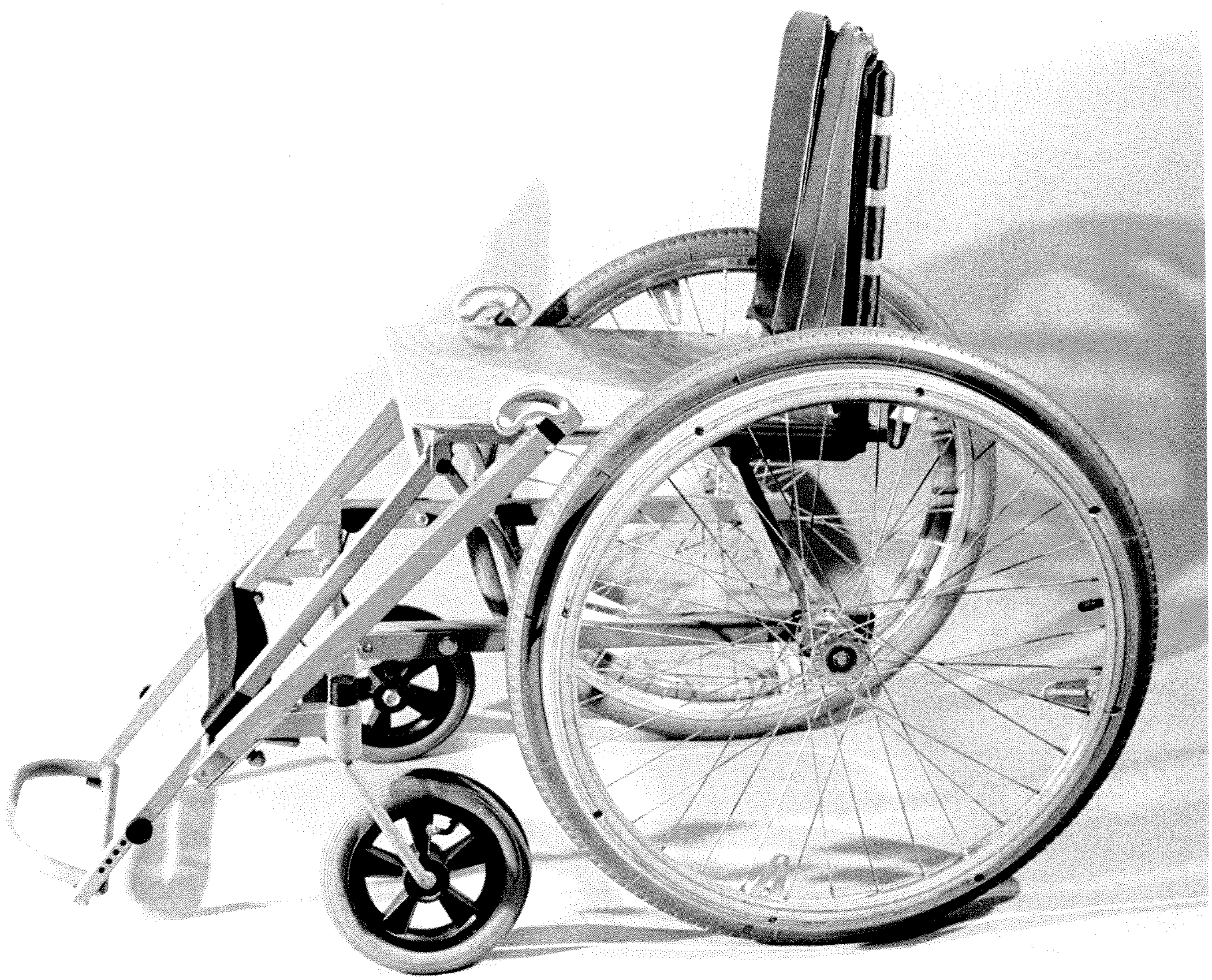

Figure 3a.
University of Virginia Adjustable Seat Wheelchair: Extended.

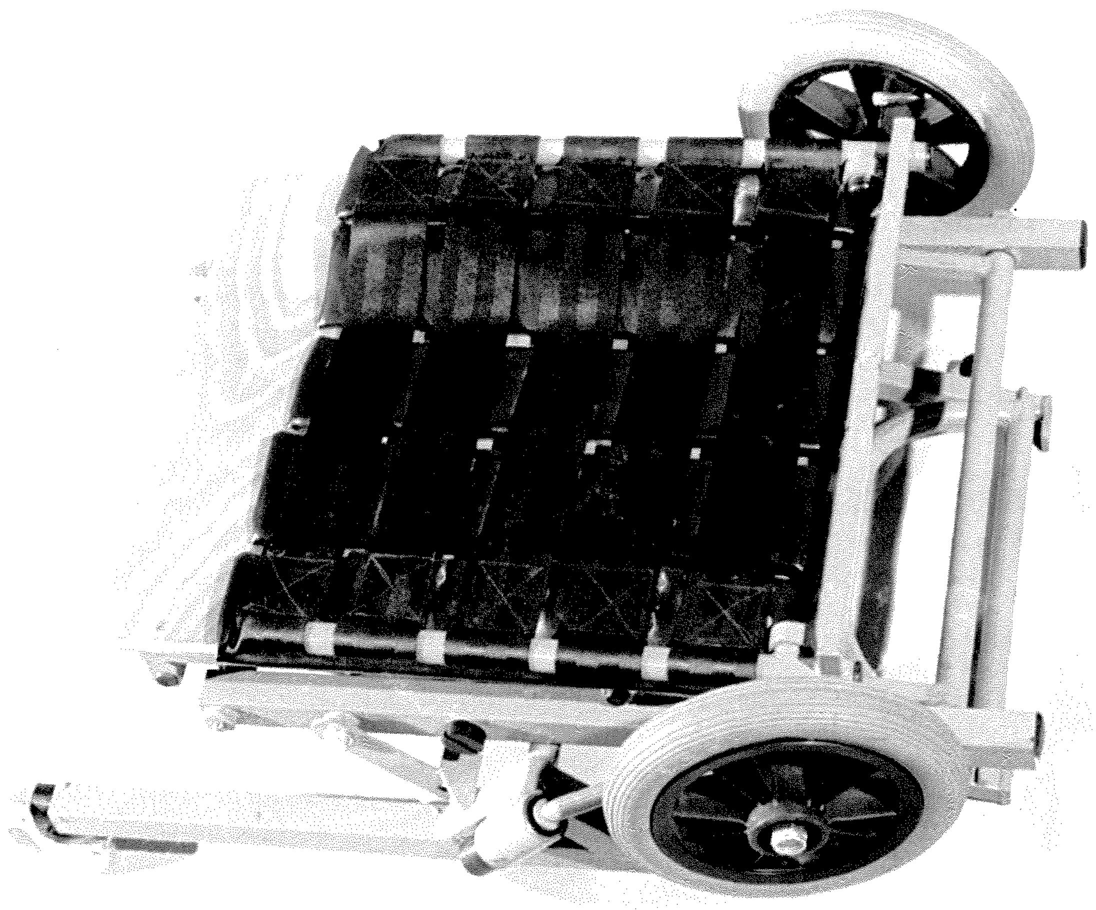

Figure 3b: Folded. This wheelchair has a frame geometry that allows the user to move the seat forward or backward through a range of 5 inches while seated. The handles at seat level just forward of the main wheels control clamps inside the frame tubes that secure the wheelchair in the selected position. The handles also provide a firm reaction point for pushing or pulling the seat to the desired position. With the wheels removed, using customary quick release axles, the wheelchair folds to a compact configuration.

for improvement, demonstrated by users and entrepreneurs, insures that new, better solutions will be sought. As with armrests, we now see examples of fold-away designs replacing the old plug-in, removable models.

Wheels

Although wire-spoke wheels are difficult to improve on from the viewpoint of strength and weight, one can expect an increasing use of mag-type wheels, probably made of reinforced plastic. The use of computer analysis allows the design of wheels for optimum strength and light weight, but the main advantages are in durability and minimum maintenance. Sealed precision ball bearings are replacing the cone type of wheel bearings for most uses.

Tires

Non-pneumatic tires made from urethane or other synthetics minimize maintenance and increase tire life span. They also approach the light weight and low rolling resistance of high-pressure pneumatic tires. However, to provide a ride comparable in comfort to pneumatic tires, some type of suspension, such as rubber mounting between the frame and wheels, may be required. The characteristics of this suspension are yet to be determined, although some work is being done in this area. Several spring casters are already on the market, but the amount of springing (spring constant) has not provided comfort without bounce, nor has it reduced stress on the frame. This is a problem that remains open to analytical and experimental study.

Brakes

A recent survey* has shown that paralyzed veterans would like their wheelchairs to be equipped with running brakes that, like a bicycle or automobile, allow the user to control the speed of the vehicle on hills and in coming to a stop (9). Drum-type brakes, like those used on bicycles and some wheelchairs in Europe, are a satisfactory solution that is available; it is up to the American manufacturers to respond.

Drive Systems

Although there are proven functional advantages to alternate drive systems, the inherent simplicity of the rim drive has an undeniable appeal. Current efforts in demonstrating lever drive possibilities should be viewed as indicators rather than comparative examples. The considerable interest in lever drive systems that has been generated in the last two years should give rise to one or more commercially available models, either as a complete wheelchair or as an add-on accessory.

POWERED WHEELCHAIRS

In December 1953, G.J. Klein at the National Research Council in Ottawa issued a report titled "A Wheelchair Electric Drive for the Use of Quadriplegics" (10). The system consisted of two geared motors driving each main wheel independently through a rubber faced pulley wheel, powered by two 12-volt batteries, controlled by a joystick operating through relays, all mounted on an Everest & Jennings manual wheelchair. The powered wheelchair in common use one third of a century later follows this same configuration and still retains a remarkably similar list of components. However, a closer examination reveals significant changes in design and construction. The frames have been made more sturdy and the wheelbase lengthened. Pneumatic tires have replaced hard rubber, mag type wheels have replaced the wire spoked wheels, and belt drives are used instead of friction pulleys. Pulse-width modulation now provides variable speed control, replacing the on-off clatter of the solenoids. Deep-discharge batteries provide longer cycle life than the automotive type and with the other features contribute a better overall performance than that found in the 1953 version.

In spite of these many improvements, for the most part the powered wheelchair is still a modified manual wheelchair. There are some exceptions. Wheelchair III, a workshop held in San Diego in March 1982 (11), addressed this problem and recommended that the powered wheelchair be based on a powered chassis upon which could be mounted a standard or custom seat and any accessories that might be needed by the user. The history and implications of this new approach to powered mobility are discussed in more detail in Chapter 6.

Some recently introduced models reflect this trend. One example is the Fortress Scientific which not only has a demountable seat, but the chassis itself can be readily separated into separate parts for lifting into the trunk of a car. Another example is the Besam, with the drive wheels in front and a seat which has powered legrests and backrest as an option. Both of these wheelchairs have abandoned the manual wheelchair frame concept and built the wheelchair from scratch, an approach that offers much more scope in improving function, comfort, durability, and appearance.

In assessing how the advantages inherent in this new approach might materialize, it is prudent to examine the possibilities in the component parts. By separating seating from the chassis, it becomes possible to provide a variety of standard seats or to fabricate custom seats that satisfy the needs and wants of particular users. Several automotive bucket seats are now available for wheelchairs offering comfort, adjustability, support, and style that goes far beyond the conventional. These seats, however, are bulky and heavy. Cost and weight are the prime concerns restricting the introduction of powered adjustments for support as demonstrated in the Besam model.

The powered chassis, once independent from the anthropometric and ergonomic considerations of seating, becomes purely an engineering problem,

*Survey based on 168 responses to a questionnaire published in the March 1985 issue of *Paraplegia News*.

and can more readily utilize up to date engineering technology in all of its parts. At present there are no apparent breakthroughs in energy storage. The deep-discharge lead acid battery is still the best solution, but the use of tubular positive plates, as has been demonstrated in Europe, can lead to a cycle life of 2,000 discharge cycles or more. Although more costly initially, they could conceivable last the life of the wheelchair. Recent improvements in chargers and battery monitors ensure a more efficient and reliable energy source, further increasing battery life and avoiding the chance of being stranded with a "flat" battery. Motors represent a long standing technology which offers little hope for improvement, except that a motor with the correct specifications can offer improvements in performance and efficiency. Motors other than permanent magnet, such as series wound motors, may offer some advantages in starting torque and are readily available in production. Pancake motors with a large diameter, low speed, and high torque are attractive but as yet are not available with specifications suitable for a wheelchair.

More important than the motor is the drive train which connects the motor to the drive wheel. Although pulleys and toothed belts will continue to be used, enclosed gearing is a more logical choice for trouble free operation. A transmission that permits a change in gear ratios could do much to improve the overall efficiency, range, and performance. A recent and very innovative automatic transmission called the Resatran has been demonstrated by Reswick (12). It is doubtful if such devices could be developed economically for wheelchair use, but if they were already in use in some other application their use in a powered chassis should be seriously considered. Motor controllers play an equally important part in determining the overall performance. The customary pulse width modulation robs the motors of some of the efficiency experienced with direct current. Power transistors are not yet available in a size suitable for wheelchair power requirements and have exhibited considerable intrinsic losses. As an alternative a voltage converter under investigation by Inigo holds some promise in providing a reliable, compact, and efficient means of controlling motor speed and torque (13).

Wheelchairs that embrace the powered chassis concept show changes in wheels and tires. Typically, the drive wheels are smaller than conventional and the caster wheels are larger. All tires are pneumatic, with wider treads for better off-pavement traction. Some models are made with the drive wheels in front and the casters in the rear. This provides more foot room and better traction over obstacles, but is inherently unstable requiring velocity feedback in the control system to avoid fishtailing. The use of some form of suspension to keep all wheels on the ground and to improve riding characteristics is also indicated.

The joystick will probably continue as a basic interface between the man and the machine, although it is far from ideal for many users. Head, voice, chin, and breath control will continue as alternative means, but all of these may benefit in the future from micro-computers that can provide a modicum of automatic control, relieving the operator of all but the grossest decisions. There are many possibilities for the future of these systems, but to be useful and effective, intimate cooperation between the electronic experts and potential users will be required. As in all other aspects of the powered wheelchair, simplicity and reliability are overriding considerations in an application where low volume, reasonable cost, and high liability govern the marketplace.

SPECIALTY ITEMS AND ORPHAN PRODUCTS

A variety of special purpose wheelchair designs have been developed in recent years. Some, such as the 3-wheeled scooter popularized by Amigo, have become a viable alternative for many users, but most fill a very limited need which makes economic development an unlikely venture.

Wheelchairs in this category include stairclimbers, both manual and powered, stand up wheelchairs, omni-directional powered wheelchairs, and all-terrain models. Specialty needs, particularly for children, include seating systems with multi-adjustments to provide comfort, function, and posture support. Some of these may be classified as orphan products and be eligible to receive subsidies to encourage manufacture. Others can be considered little more than curiosities, satisfying the special desires of only a few people.

SUMMARY: THE FUTURE

Emerging from the recent advances in wheelchair technology and the availability of inexpensive imported wheelchairs, is a marked distinction between commodity, or occasional use wheelchairs, and prescription-type wheelchairs that serve as an integral part of a user's lifestyle. Continued development of the prescription chair is needed to meet the varied requirements of persons with different disabilities, abilities, needs, and activities. Seating comfort is perhaps the greatest need, and only recently have models become available that offer any adjustability. Mobility in confined spaces is another requirement that needs attention. Propulsion systems other than handrims, such as levers, are receiving wider attention. Ease of transferring to and from various situations needs to be addressed.

Further development in material and structural design can reduce the cost and increase durability for the lightweight chair. Mag-type wheels that are as light as wire spoke wheels are one example of a possible technical improvement. Another example are the trouble-free tires with good ride and low rolling resistance.

The power base concept is taking root and with it the promise of greater reliability and overall performance. Seating options for a power base offer many possibilities, from simple lightweight folding seats to fully adjustable power seats. Custom contoured seating using CAD-CAM is a real possibility in the next few years.

Controls for powered wheelchairs are still in the early stages of development. Smooth, accurate control of the dynamic aspects of the wheelchair in all situations is the goal for all types of inputs and should be pursued.

At the present time, the wheelchair manufacturing industry itself seems to be undergoing a period of rapid change with many new ideas, designs, and concepts presented to a small but diverse clientele. One can expect a sorting out in the next few years, with the more practical innovations becoming the standards for the future.

It is hoped that this future includes a marketing system that allows a customer to choose from a variety of components that can be assembled to provide a machine that suits the size, function, and appearance desired, as well as the prospect of immediate delivery. Providing a suitable, reliable product without delay and at a reasonable cost should be the main goal of research in the wheelchair industry.

ACKNOWLEDGMENTS

The photographs and drawing presented in the figures of this article were provided by the University of Virginia Rehabilitation Engineering Center.

REFERENCES

1. **Gordon RC, Kooistra PG, Hamilton LR:** A needs assessment study of physically handicapped individuals in Charlottesville and Albemarle County, Virginia. *University of Virginia Rehabilitation Engineering Center, Report No. UVA-REC 108-84*, 1984.
2. **Paralyzed Veterans of America:** *Adult Wheelchair Users Survey*. Bethesda, MD: Paralyzed Veterans of America, 1982.
3. **Stamp WG, McLaurin CA:** *Wheelchair Mobility: A Summary of Activities During the Period 1983-1984*. Charlottesville, VA: University of Virginia Rehabilitation Engineering Center, 1984.
4. **Stamp WG, McLaurin CA:** *Wheelchair Mobility: A Summary of Activities During 1985*. Charlottesville, VA: University of Virginia Rehabilitation Engineering Center, 1985.
5. **Hobson DA, Shaw GC, Monahan LC, Chung KC, McLaurin CA:** *Anthropometry for the Physically Disabled, Volume I: Cerebral Palsy*. Memphis, TN: University of Tennessee Rehabilitation and Engineering Center, 1987.
6. **Kauzlarich JJ, Thacker JG, McLaurin CA:** Wheelchair tire rolling resistance theory and tests. *University of Virginia Rehabilitation Engineering Center, Report UVA-REC 102-85*, 1985.
7. **McLaurin CA:** An anti-shimmy damper for wheelchair casters. In *Proceedings of the 9th Annual Conference on Rehabilitation Technology* 6:288-289. Washington, DC: Association for the Advancement of Rehabilitation Technology, 1986.
8. **Coe PL Jr:** Aerodynamic Characteristics of Wheelchairs. *NASA Technical Memorandum 80191*, 1979.
9. **Thacker JG, Seelye BA, Kauzlarich JJ:** Engineering Analysis of Manual Wheelchair Brakes. *University of Virginia Rehabilitation Center, Report No. UVA-REC 101-86*, 1986.
10. **Klein GJ:** A wheelchair electric drive designed for the use of quadriplegics. *National Research Council of Canada, Report No. MM-234, 1953.*

11. **Golbranson FL, Wirta RW (Eds.):** *Wheelchair III. Report of a Workshop on Specially Adapted Wheelchairs and Sports Wheelchairs*. Bethesda, MD: Rehabilitation Engineering Society of North America, 1982.
12. **Reswick JB:** Automatic transmission for electric wheelchairs. *J Rehabil Res Dev 22(3):42-51, 1985.*
13. **Inigo RM, Tsoi D:** Two-quadrant feedback PWM DC-DC converter for wheelchair motors. In *Proceedings of the International Conference of the Association for the Advancement of Rehabilitation Technology, Montreal*, 258-259. Washington, DC: Association for the Advancement of Rehabilitation Technology, 1988.