VARIABLE-HEIGHT-POWERED WHEELCHAIR FOR THE QUADRIPLEGIC DRIVER

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FOREWORD

Originally the charge, under the SRS, was for us simply to improve on the mobility system for severely handicapped people. We interpreted this to include short-range travel, long-range travel, inside and outside, as well as horizontally and vertically. In short, any transport system which would help in daily activities, job execution, or recreation was to be considered. A few hundred man-hours were spent on preliminary design of an easily accessible special "automobile" which would accept a severely handicapped [a] person sitting in a standard powered (say E&J) wheelchair at driving position. Jerome Sills, a post-polio partial quadriplegic, was at that time (1967) driving a dropped-floor 1954 Ford Sunliner from a wheelchair. When it became obvious that a special wheelchair-compatible automobile would cost several times more than a standard automobile, this approach was discontinued. Assume that a standard auto costs $4,000, that the special auto, or greatly modified one, costs at least $10,000, and that the special auto is of little use to anyone other than the handicapped driver. This means that if we could somehow eliminate the need for the special auto — or its modification — we would have $6,000 to use for an alternate system. The obvious alternate system is a variable-height wheelchair which will fit in a standard automobile or van. A unit bid on these wheelchairs of $4,100, on the basis of three units, has just been received. This leaves $1,900 for some sort of lift or other entry system. A standard van-type tailgate lift costs under $500.

[a] Ultimately a "severely handicapped" person was considered to be a C-5 quadriplegic.

More money (perhaps the full $1,900) would be needed for a lift for a standard auto. There appears to be no choice economically between going the special vehicle-standard wheelchair route as against the standard vehicle plus lift — special variable-height wheelchair route (note that the $10,000 cost estimate for the special auto may be low by 50 percent). However, when an appraisal of the tremendous expansion of daily activities possible through the exploitation of a variable (seat) height wheelchair is made, the choice is unequivocally in its favor. The possibility of a 17 in. increase in vertical reach — from 7 to 50 in. above the floor to 0 to 60 in. above the floor — is a very attractive (50 percent) one. This was the germination of the variable (seat) height wheelchair concept.

So attractive became the concept of mobility enhancement through variable wheelchair seat height that the VA asked us to push through the wheelchair, holding up development of the auto lift and driving equipment. Limited production of the wheelchair began in the fall of 1974.

HISTORY

Introduction

Prior to the initial funding of this project by SRS, Peter Bray wrote a survey thesis (1), which was published in part (2), wherein he outlined the mobility problems of severely handicapped people and also included a comprehensive state-of-the-art survey on quadriplegic functions, wheelchairs, vans, lifts, special autos, and hand controls. Mr. Bray (1) was also the first person to suggest a variable-height wheelchair.

The present UC wheelchair project was initiated by Peter Bray, C.W. Radcliffe, Biomechanics Laboratory; Jerome Sills, a post-polio partial quadriplegic, driving a 1954 Ford from a wheelchair; and D.M. Cunningham.

Special, Custom Designed Vehicles Accepting Standard Wheelchairs

In 1957, Jerome Sills supervised the modification of a 1954 two-door Ford Sunliner (1) to accept his junior manual wheelchair. He had the right front seat removed and the floor there lowered to 3 in. above the ground. He entered via the right front door by running his wheelchair up a 3 in 12 (14.5 deg.) ramp onto a turntable. Manually rotating the turntable placed him in right-hand driving position. Right-side steering wheel and hand controls enabled him to drive. Mr. Sills drove this vehicle for several years (until his death in 1970); he was fairly satisfied with it even though the structural integrity of the auto frame was in quesiton and the 3 in. ground clearance was unsafe.

In 1964, under the British Polio Fund, Mr. Leslie M. Ballamy (3) developed a system consisting of a manually adjustable height wheel-

chair and a high-roofed, tilting-floor vehicle. Using this system, a paraplegic could handcrank the wheelchair seat (with a force per stroke of 15 percent of body weight) from normal height down to a seat height of 10 in. The floor of this front-drive, Citroën suspensioned vehicle could be tipped back so that the rear tailgate (acting as a ramp) touched the ground. Easy rear entrance was possible — or side door entry — via a short ramp to the curb, by tipping the vehicle laterally. This was a good idea, but the expense of the body and suspension modification and the fact that paraplegics can normally transfer out of their wheelchair to an auto seat limit its application.

A short magazine article in 1966 made reference to a modified four-door Renault auto in which the top had been raised and the floor lowered for entry in a standard wheelchair. This is parallel to the Sills solution, except that between the years 1954 and 1966 auto top heights were lowered by 8 to 12 in., necessitating roof raising in addition to floor lowering. The trick here is to position the lap of a wheelchair occupant at a level just below the steering wheel. Again, this double modification is very expensive, reduces structural integrity, and spoils the esthetics of the vehicle.

About 1967, Mr. Fred Taberlet (4), a mechanic in southern California (now deceased), developed an unroofed front-wheel drive vehicle in which the whole inner floor from fire wall to rear and wheel to wheel could be lowered to the ground for wheelchair entrance. Although the auto was underpowered and the top remains unfinished, this vehicle was well adapted for drivers in standard wheelchairs.

On the UC project in 1968, Mr. David F. King conceptualized two 8-ft.-long, high-roofed, low-floored commuter-type vehicles for wheelchair-bound drivers: 1. a rear entry front-wheel drive vehicle and 2. a front entry (like the Isetta auto) rear-engined vehicle. The idea was to park at right angles to the curb with the entry end overhanging the curb — allowing ramp entrance. With wheels butting the curb, the extreme outer end of the vehicle was 7 ft. from the curb, which is probably legal. The expensive requirements of a completely customed body, special suspension, ramp extender, etc., precluded the development of these autos. Normal commuters might buy them — except for the awkward, high tops.

Standard Vans for Wheelchair Drivers

Many quadriplegics have adapted standard automatic-powered-step vans like the Metro (GM) 404 (1) for driving from an ordinary wheelchair by adding a tailgate lift, removing drivers seat, and covering up the standing step. This is a good solution. Not only is the cost of these vans comparable to a medium-priced automobile, but also the modification costs are minimal ($1,000–$3,000). The only disadvantages are the size,

height clearance in garages, awkwardness, and the question of future availablity of this type of van.

Alternatively, wheelchair-bound quadriplegics have decided on the newer Econoline (Ford), Dodge or Chevrolet vans. Each of these has the engine positioned forward and the right center, allowing a wheelchair space at the driving position. However, these vans have a relatively low top so that a full-sized person in a full-sized wheelchair has serious problems with head clearance and visibility. One partial solution is to build into the floor two sloping wheel wells which will drop the wheelchair 3½ in. (limited to this depth by the lower longitudinal wheelchair frame bars). This depth is insufficient for a medium-to-tall quadriplegic. Greater depression of the wheelchair has been acheived at Robin Aids (Vallejo, California) by building into the van floor a 26 in. × 48 in. elevator having a 10 in. vertical excursion. Although adequate, this is a very expensive scheme, and some types of vans have frame members in the way of the modification. A plus factor is the automatic collision restraint of the wheelchair by virtue of its containment in a "well."

Hand Controls for Auto or Van Driving

If the wheelchair is positioned correctly with respect to the steering wheel, most low-level quadriplegic occupants can drive with standard push (brake)-pull (accelerate) hand controls if the vehicle has power steering, power brakes, and automatic transmission. However, with an interfering wheelchair-vehicle interface, and/or with a high level (say, C-4—5) quadriplegic, a different driving control system is desired. Charles Scott (UCLA) has developed a small joy stick (like a Motorette unit) device for steering, braking, and accelerating, which can be mounted anywhere. Dr. Paul Newell (Texas A&M) is working on a related control system. Several American auto manufacturers have in prototype stage simple wrist twist (1) or pistol grip steering systems. All of the control systems mentioned have all switches located very near the steering unit, within easy reach. Volvo will market such an option in 1975.

Tailgate-Type Lifts for Vans

Several companies make standard lifts which can be rear- or side-mounted on a van. A 500-lb. capacity type is quite adequate for a powered wheelchair and heavy person. Standard units which fold flush outside the doors cost from $410 installed to $900 installed. Custom units which fold inside the doors when not in use cost $250 to $400 more, installed. In either type a small (4-6 in. long) ramp must be provided to allow the wheelchair to roll up over the thickness of the lift floor and a restraining lip provided which prevents the wheelchair from rolling off.

A loading ramp is another possibility, but unless the van floor is low

(e.g., Mercedes front drive) or the doors are next to a high curbing, a long (16–20 ft.) ramp is necessary to accommodate the 24 in. floor height (Table 1) and low wheelchair power.

TABLE 1.—*Size Comparison Between UC Wheelchair and a Standard E&J Wheelchair (with the same 5'8" person as in Fig. 1-9)*

Dimensions, in.	E&J[a] Premier 16" adult wheelchair seat ht. 18"	UC Wheelchair Configuration: Normal seat ht.[b] 18" (Fig. 2)	Maximum seat ht.[b] 27" (Fig. 1)	Lowest seat ht.[b] 10" (Fig. 3)	Reclining backrest seat low (Fig. 4)
Overall length[c]	46.5	54.5	39.5	58.3	71.5
Overall width	23.3	24.5	21.0	24.5	24.5
Vertical clearance[b] (for a 6'0" tall person)	51.0 (53.0)	49.5 (51.5)	60.0 (62.0)	42.3 (44.3)	23.5 (23.5)

[a] Has overall dimensions comparable to the E&J power-drive chair.

[b] Seat heights measured from floor to the top rear of the 3 in. cushion.

[c] Extreme of frame, toes, head, etc.—as appropriate.

Automobile Lifts for Wheelchairs

There are several types of commercially available auto-mounted lifts (such as Hoyer or Trujillo) which allow paraplegics, or quadriplegics with an attendant, to lift themselves through the use of a sling out of their wheelchair into the front auto seat; the folding manual wheelchair can then be placed behind the front seat. No provision is made for handling a heavy, powered wheelchair.

Given the constraint of keeping the quadriplegic in the wheelchair seat while in the automobile, there would appear to be only two more viable possibilities: 1. have a Hoyer-type device lifting the seat and occupant separately from the wheelchair base or 2. lift the man and the whole wheelchair into the auto. At least half of the front seat of the auto would have been removed. In case 1. there still remains the problem of what to do with the wheelchair base — unless one was located at every destination. The case 2. solution would seem more expedient, however difficult. Considerations such as door height, head clearance, floor space, drive shaft tunnel, desirability for loading on curb side and driving from the left side, and interference between lift, wheelchair, person, and auto controls are some of the problems which must be overcome.

A partial scheme for auto loading of a manual wheelchair and occupant (5) consisted of an unpowered wheelchair with four 10-in. wheels or

two 6-in. castor wheels and two 20-in. removable (locked on by two toggle clamps) rear wheels. Here the wheelchair is wheeled up to the left side of a small sedan (with its left front "bucket" seat removed). The paraplegic occupant manually pulls a hydraulic lift out of the auto which he connects to the right side of the wheelchair seat. Manually he pumps up the cylinder which lifts himself and the wheelchair free of the ground. If necessary (with the 20 in. rear wheels), he removes the chair rear wheels and places them in a special rack in front of the back seat. Now, he simply maneuvers his legs into the auto and manually rotates the pivoting arms of the lift and wheelchair into driving position. It is a very neat and compact package requiring no power source — a great solution for a paraplegic who does not want to transfer himself out of the wheelchair. It would be next to impossible to operate on a sloping street. This is not a solution for quadriplegics because it requires manually pumping the hydraulic unit and it will not accommodate a powered wheelchair.

The UC group has operated two auto-lift prototypes (6). One successfully placed a manual wheelchair into the right side (from the right ground position) of a 1967 two-door Corvair. Its disadvantages were: 1. a manual operation similar to Mühlemann's (5) was required for swinging wheelchair and unit into the auto (prohibitive on a side slope) and 2. the vertical clearance sacrificed (about 5 in.) by having the supporting tracks under the wheels (not the case with the Mühlemann solution) was prohibitive for a tall person. The other placed a crude variable-height-powered wheelchair in the driving position of a 1965 Ford two-door sedan, starting from the right ground side position. This was a bigger challenge but the lift had the same vertical clearance drawback as its predecessor.

A more recent approach at UC (6,7), overcomes all of the shortcomings of previous lifts. In this concept the UC variable-height wheelchair would be backed up to a two-door sedan with right door open and lift extended. Two forks on the lift would fully engage grooves under the wheelchair seat. "Lowering" of the wheelchair seat, since it was restrained by the forks, would cause all four wheels to retract upward about 10 in. A single control switch would actuate the powered lift mechanism which would program the wheelchair and occupant through the auto door, over the drive shaft tunnel, rotate the chair, and push it up into driving position. Alternately, the wheelchair could be programed into right-front passenger position. The original front seat of the auto would be removed, but no structural modifications of the vehicle would be necessary. Locking the wheelchair to the lift would provide accident safety. This automatic, programed lift is in limbo, at a point somewhat beyond the preliminary design stage.

Powered Wheelchairs

This is undoubtedly the broadest topic to be considered here. Even if we limit the discussion to 3- and 4-wheel, off-highway, single-occupant vehicles, the topic is very broad. At one end of the spectrum we have an almost completely paralyzed person driving a powered bed or guerney at 3 m.p.h. by mouth blowing, speech, or moving his eyes. At the other end of the spectrum we have an apparently normal person joy riding in a one-person golf cart-type tiller steering "wheelchair" at 45 m.p.h. Nearer the front of the spectrum is the low-level quadriplegic driving a modified battery-powered wheelchair via a joy stick control unit. No argument will be made to promote the use of wheelchairs. Clearly some handicapped people do need wheelchairs, until a better substitute comes along, and the number of people needing powered wheelchairs will probably increase as handicapped people age and/or their diseases (e.g., multiple sclerosis or muscular dystrophy) progress.

Only a cursory coverage of battery-powered wheelchairs will be given here. These are vehicles which can be used safely (and legally) inside any building, size permitting, as well as from a few blocks to a few miles outside on a relatively smooth surface (e.g., on a lawn, but not a plowed field). The d.c. motor, belt-driven, battery-operated system is completely self-contained on the wheelchair; periodic battery charging (usually daily) is required. A basic powered wheelchair is the E&J manual (originally folding) type to which has been added: 1. two rear-mounted permanent magnet (RAY) d.c. motors and 2. one or two 12-volt auto or golf cart batteries. The latter are larger but can be drained (discharged) to a lower voltage level many times more than a standard auto battery. Exotic batteries, such as nickel-cadmium, can be used, but they cost five times as much. Also included is a speed control and "steering" unit. A "joy stick" in forward position produces maximum forward speed using both motors at maximum speed; rearward position produces full speed in reverse; sideward stick motion runs one motor faster than the other, turning the wheelchair. A big advantage of this scheme is that the wheelchair can turn about its own axis. The seat is either stretched plastic or a board with a foam rubber cushion. Advanced Wheelchair, Stainless, Motorette, and many other companies, also make similar wheelchairs. Some have a more rugged nonfolding frame designed specifically for motor power. None of these provides for varying seat height, back reclining, feet retracting, or width narrowing.

Compass Industries and the E&J Mark 20 are examples of golf-cart type, single occupant, powered chairs. They can be set up for top speeds anywhere from 4 m.p.h. to 40 m.p.h. The low-speed version will climb a steeper grade than the high-speed version. Addition of a gear changer

increases hill climbing ability and/or speed range. Both of these wheelchairs (compared to the more conventional handicapped chair) are larger, heavier, more powerful, covered cosmetically, and have positive tiller steering and dynamic braking. Probably this oversized-tire type should be considered an outdoor but nonhighway-type vehicle. It is too large and bulky and has too large a turning radius for most inside uses.

Another outside-type vehicle is the Swedish Permobil (8). It has large (16 to 22 in.) pneumatic-tired wheels, enabling it to negotiate a plowed field or even a short course of 4 in. × 16 in. steps. The backrest reclines and leg rest extends independently. However, the seat is at a permanent 24 in. height and this vehicle is also large, heavy, and has a larger turning radius than the conventional wheelchair. It may possibly be a little over-designed, since it has seven actuators for the several mechanisms.

In the originality department, there is a paraplegic veteran at the VA hospital in Wichita, Kansas, who wheels his manual chair up to the side of an ordinary motorcycle, clamps the armrest to the motorcycle, and drives away at 25 m.p.h. through use of hand controls on the motorcycle (note: some motorcycles have the shift lever, as well as other controls, on the handle bars). This speed is extremely high for a conventional wheelchair.

Wheelchair Controls

The most widely used speed control system for powered wheelchairs, in conjunction with the joy stick forward, reverse, left, right unit, is the Motorette d.c. pulse-width-modulation unit. This solid state electronics unit sends longer and longer pulses to the d.c. motor as the joy stick is deflected. It is a smooth and very efficient unit.

Caster Wheels

The caster wheels used with the Motorette unit create some problems: 1. conventional caster wheels shimmy (wobble back and forth) at about 4-6 m.p.h. This can be minimized by a low friction "clamp" around the pivot axis but may crop up later as the clamping force decreases; 2. Casters are easily deflected as they go over an obstruction, such as a sidewalk edge and some time is required before the joy-stick system can correct the false path. A positive type, e.g., tiller or "steering wheel" type, would not have this limitation.

Positive Steering

Tiller-type steering is much more stable and safe, especially for speeds above 4 m.p.h., but the range of hand motion is too great for a quadriplegic to handle manually, say ±4 in., with the force that he can develop, say ±3 lb. Steering motors, one on each "castor" wheel, with electronic control, would solve this problem.

Reclining Wheelchairs

In any skin ulcer prevention program it is good to have a reclining backrest to shift the weight at least partially off of the buttocks. The Swedish Permobil (8) has a powered reclining backrest. Also, the Rugg (9) wheelchair, which is similar to the Permobil, has a reclining backrest. A group at Utah State University (10) has developed a versatile wheelchair (mobile platform) with a reclining backrest; it will recline at any position of the variable-height seat.

Supporting Surface

The buttocks of the human body were not evolved for sitting on—at least not for prolonged periods. When the whole body weight of a normal person is supported by the buttocks on a flat surface the mean pressure is about 25 mm. Hg. (11); maximum pressure (under the ischial tuberosities) is about 120 mm. Hg. (11). The average blood pressure in the arterioles is 70 mm. Hg. (14). Average pressure in the capillaries is 35 mm. Hg. (14) and only 15 mm. Hg. (14) in the small veins. So, even with an "optimum" cushion design (where we would have mean pressure (25 mm. Hg.) all over the bottom of buttocks and legs) there would still be a circulatory problem with venous return. Any design allowing a pressure buildup anywhere greater than 35 mm. Hg. would greatly reduce blood supply. Limiting the blood supply, plus such factors as traction on the skin, local humidity, or skin temperature buildup, will tend to kill the skin and underlying tissue. Clearly, any "cushion" other than the perfect one causes pressure which cannot be sustained long. Even the optimum one causes problems.

To date, in order to guarantee the prevention of decubitus skin ulcers with any seat cushion, the buttocks pressure must be relieved periodically. Quadriplegics in wheelchairs are trained to do "pushups" by lifting up their upper body with elbows on the armrests or by leaning as far forward (head to knees) as possible with elbows looped through straps connected to the backrest. Another viable solution, which has other advantages, is the reclining back arrangement of some wheelchairs. A reclining back not only reduces the net buttocks pressure by an acceptable factor of 1/3 to 1/5, but this action, as well as that of an articulating footrest, maintains some of the tone desired in the paralyzed muscles (e.g., reclining the wheelchair backrest and leg rest periodically is a substitute for "range of motion" exercises necessary to keep joints from stiffening).

Variable-Seat-Height Wheelchairs

A group of engineers at the University of Utah (10) have developed a "mobile platform" which has a seat that can be raised from normal (18

in.) height to table height, where the backrest can be reclined for transferring to guerney or operating table. It is a good device for hospitals but would be limited in daily activities for lack of a second (lead-acid) battery and the need for a lower seat height for van transport and reaching a hand to the floor.

The Motorette Corporation has recently marketed a small, highly maneuverable Capp Cart (15) wheelchair with a seat capable of being elevated from normal (19 in.) to a 27-in. maximum. All wheels are 8 in. in diameter with solid rubber tires, limiting the wheelchair to smooth surfaces and low speeds. No footrests are included since the chair was designed for limbless (e.g., thalidomide) children. These could be added, however. It also has only one lead-acid battery, which limits its range. Mr. James Allen of Wheelchairs, Inc., has developed a similar variable-seat-height wheelchair (16). An important modification, consisting of an articulated footrest, was added to this by Mr. Charles Scott of UCLA.

All three of these variable-seat-height wheelchairs have the same drawback: the lowest seat position is limited to about ordinary chair height because the ball screw or hydraulic lifter is located in a vertical position under the seat. It would be very desirable for the seat to go down another 8–10 in. so that the occupant could reach the floor with one hand and fit into a low van or automobile while in the wheelchair.

Curb-and Stair-Climbing Devices

Possibly the greatest architectural barriers to wheelchairs are stairs and curbs. Even with the aid of one or two attendants, carrying a person in a powered wheelchair up several building stories is impractical, if not impossible. Lifting the wheelchair over a curbing is hard enough. In most residential areas there are enough driveways per block to enable a wheelchair user to traverse from sidewalk to sidewalk without going over a curbing. In many downtown areas there are no driveways and the convenient curb ramps for wheelchairs have not been put in. Unfortunately, the heavier the wheelchair (and occupant), the more desirable it is to have a curb ramp (or nearby driveway) or a curb-climbing device on the wheelchair. Present curb climbers or concepts are awkward, heavy and expensive, but can be made relatively safe to use. Conceptual stair climbers, on order of magnitude, are complicated (12), particularly if all sizes of stair risers and length of runs are to be accommodated. Stair-climbing safety is another matter; a failure or slip at the top of a stair run could be catastrophic. A limited solution for a given stairway is the personal elevator; transfer from wheelchair to "elevator" is a severe problem and the empty wheelchair must somehow be gotten up the stairs (or two chairs used). For the most part wheelchair users, without access to ramps or regular elevators, are confined to the first floor.

Wheelchair Transfer

One of the biggest problems of a quadriplegic is transferring into and out of a wheelchair to bed, toilet or toilet chair, bath tub, guerney, or any other sitting or lying appliance. The problem is minimized for a small- to medium-sized handicapped person with one attendant. A large person has a much greater problem and may need two attendants on occasion. Various Hoyer-type cranes or mechanical aids can partially replace attendants. Ideally the transfers can be made with a minimum of assistance—except possibly some passive overhead hooks, straps, or ropes.

Since the safest transfer path is sideways from the wheelchair, even for "falling" out of or into the wheelchair, no obstructions should prevent themselves in this path, either on the wheelchair or appliance transferred to. It would be of great assistance if the seat of the wheelchair could be raised to a level somewhat higher than the surface being transferred to and vice-versa.

THE UNIVERSITY OF CALIFORNIA VARIABLE-HEIGHT WHEELCHAIR

Background Steps

1. The concept of a specially designed custom-made vehicle which would accommodate a conventional wheelchair and occupant, as driver or rider, was rejected as being:
a. Too expensive.
b. High (over 6 ft.) and awkward.
c. Having no other function (not useful for nonhandicapped people).
2. A lift concept for placing the variable-height wheelchair and occupant into a standard American two-door sedan was deferred until the UC wheelchair went into the production phase.
3. A curb-climbing wheelchair concept was deferred as having a lower priority than other daily activities.
4. All efforts were directed toward finishing the UC powered, reclineable, adjustable-height, and narrowing (PRAHN) wheelchair, with the design emphasis on daily activities in the home, work place, recreation area, going short distances on relatively hard smooth surface outdoors, and transporting wheelchair and the quadriplegic in a standard van with ample head clearance, good visibility, and good driving capability.

Design Constraints for the UC Daily Activities PRAHN Wheelchair

1. It must be *no larger than a conventional manual wheelchair* with minimum weight compatible with the listed functions.
2. It must have *maximum possible continuous variation in seat height* limited

only on the low end by the height of the batteries under the seat and at the high end by the greatest extension of the seat supporting mechanism. Elevating actuator must be self-locking.

3. It must *present no lateral obstructions to body transfer* on either side for as much of the seat height range as possible.

4. It must have *adequate speed*, grade-climbing capacity, and adequate acceleration.

5. It must have the *maximum possible battery range* compatible with other constraints.

6. It must have a *minimum turning radius.*

7. It must be as *stable as possible* at all heights (e.g., have an optimum center of gravity location and/or motor acceleration and speed limiter at the high seat heights).

8. It must be capable of *passing through a public toilet stall door.*

9. It must, incidentally, *give the occupant maximum vertical mobility* or reach (e.g., from the floor (without leaning over) to light switches, wall phones, above-sink cabinet shelf, etc.).

10. It must allow the closest possible *frontal approach* to a vertical wall.

11. It must *fully extend legs and back* (e.g., recline) in at least one position for resting and relief of buttocks pressure.

12. It *must be durable and trouble-free.*

13. It must be *compatible* in size, maneuverability, head clearance, and visibility *with the standard "Big Three" vans* and the checker sedan. (These are the modern vehicles, like Ford Econoline, with windows all around, side and rear doors, flat floor, power equipment, and automatic transmission. In the vans the engine is situated in front, forward, and 6 in. to the right of center. The latter arrangement allows positioning the variable-height wheelchair at the steering wheel.

14. It must be *adjustable in size* to 90 percent of the adult population.

15. Clearly, the overriding consideration is that, if the UC wheelchair is to be accepted by a large segment of the physically handicapped population, it must provide for superior performance in the area of *daily activities.*

16. Stated another way, this wheelchair would be one in which a handicapped person could *sit during most of his waking hours.* So it would be used inside the home, office (or other work place), for recreation, and limited outside (on sidewalk or road shoulder) travel. Long distance travel would hopefully be accomplished with the handicapped person sitting in the UC wheelchair placed in a van in driving or passenger position or in an airplane, train, or ship.

17. *Wheels*

a. Front wheels must be caster (for two-motor, tank-type push) types of 8 in. diameter or less, in order to clear the batteries and linkage with the seat low.

b. Rear wheels must be 16 in. in diameter or less in order to clear the armrest with the seat low (Fig. 3) and for unobstructed lateral transfer.

18. *A minimum number of actuators* would carry out all mechanical functions except for propulsion.

19. The basic seat-leg rest must be securely *clamped to the transport vehicle,* and the occupant strapped to the seat or to the floor. This restraint system must withstand a 20 g impact loading (front to rear).

20. The raising-lowering mechanism should have *pseudo pivots* at the occupant's knee and hip joints to prevent any pulling or bunching of the clothing during seat raising or back reclining.

21. *Standard,* commercially vehicle, durable *parts* should be used as much as possible.

GEOMETRIC AND FUNCTIONAL DESCRIPTION OF MARK IV (1974) UC POWERED VARIABLE-HEIGHT WHEELCHAIR (PRAHN)

A first impression of the UC wheelchair is that it is conventional in many respects (Fig. 1–9). It has four wheels—two small castors in front and two larger individually-driven rear wheels. A standard Motorette pulse-width-modulation, joy stick speed control and "steering" unit is used. The chair itself has a flat, cushioned seat and a separate, curved metal backrest. In other respects the UC wheelchair is nonconventional in that it is powered, reclinable, adjustable-height and narrowing, hence the acronym PRAHN. When the seat of the wheelchair goes up, everything else moves in: the footrest moves back under the seat and the tread (front and back) narrows. When the seat moves down the reverse occurs (tread widens and footrest extends) until finally, at the bottom of seat travel, the backrest reclines. One ball screw actuator does all of this. An unconventional bevel gear device unit is used for positive drive and because of the great restriction on the places and orientations where the drive motors could be situated.

A detailed description of the UC wheelchair follows. This is organized so as to indicate item-by-item how the design constraints were satisfied.

1. *Dimensions and weight:* Pertinent dimensions of the UC wheelchair in the various configurations are given in Table 1 where they are compared to those of a standard E&J wheelchair. For comparison, some related van and Checker Auto dimensions are given in Table 2. Notice that a 6 ft. person in the conventional E&J wheelchair would barely clear the van ceiling when inside, would have to cock his head greatly to clear any van door, and could barely see under the top of the windshield (eye level is 5 in. below seated head height). The 21 in. × 39.5 in. vertical projection of the UC chair at maximum seat height allows turning around in a 40 in.

hallway and a standard 22 in. wide toilet stall door can be entered easily. Any horizontal barrier 24 in. or more high can be passed under with the backrest reclined. Wheel choices, besides these being commercially available and rugged, were based on the fact that "standard" 8 in. castors were the largest possible which would pivot 360 deg. at all seat heights and clear the mechanism, and the 1¾ in. × 16 in. pneumatic Sting-Ray bicycle wheels have some cushioning properties and are the largest possible for easy, unobstructed lateral transfer at normal (and above) seat height (Fig. 2) and they allow unobstructed lateral arm (elbow) movement (Fig. 3 and 4) at all seat heights. The seat cushion width is 16.5 in. The inside dimension between armrests is 17 in.; 2 in. can be added if an attendant simply removes the armrests (two bolts) and interchanges them. The penalty for the latter adjustment would be that the overall width range would now vary from 25 to 23 in. (25 in. to 21 in. before). Ninety-five percent of the population can be accommodated through the adjustable single-center-post footrest. Variations in individual thigh lengths are taken care of by moving the lower end of the sliding seatback forward and back. The headrest, essential for reclining and preventing automobile whip lash, will be universally adjustable. Swing-away armrests have up-down and inclination adjustment mechanisms. The weight of the wheelchair shown in the figures is 256 lb. Anticipated minor modifications will not change the weight appreciably.

TABLE 2—*"Big Three" 1973 Van Dimensions* (inches)

	Chevy 110	*Ford E100*	*Dodge B100*	*Checker Sedan* (Flat Floor)
Floor-Windshield top (visibility)	47.0	46.4	47.0	43.0
Maximum inside height	53.8	53.4	53.2	44.8
Rear door opening height	48.8	47.4	47.2	—
Side door opening height	49.2	47.4	47.2	42.8
Overall height	80.0	76.0	80.8	62.8
Floor height	25.0	22.0	27.0	14.5

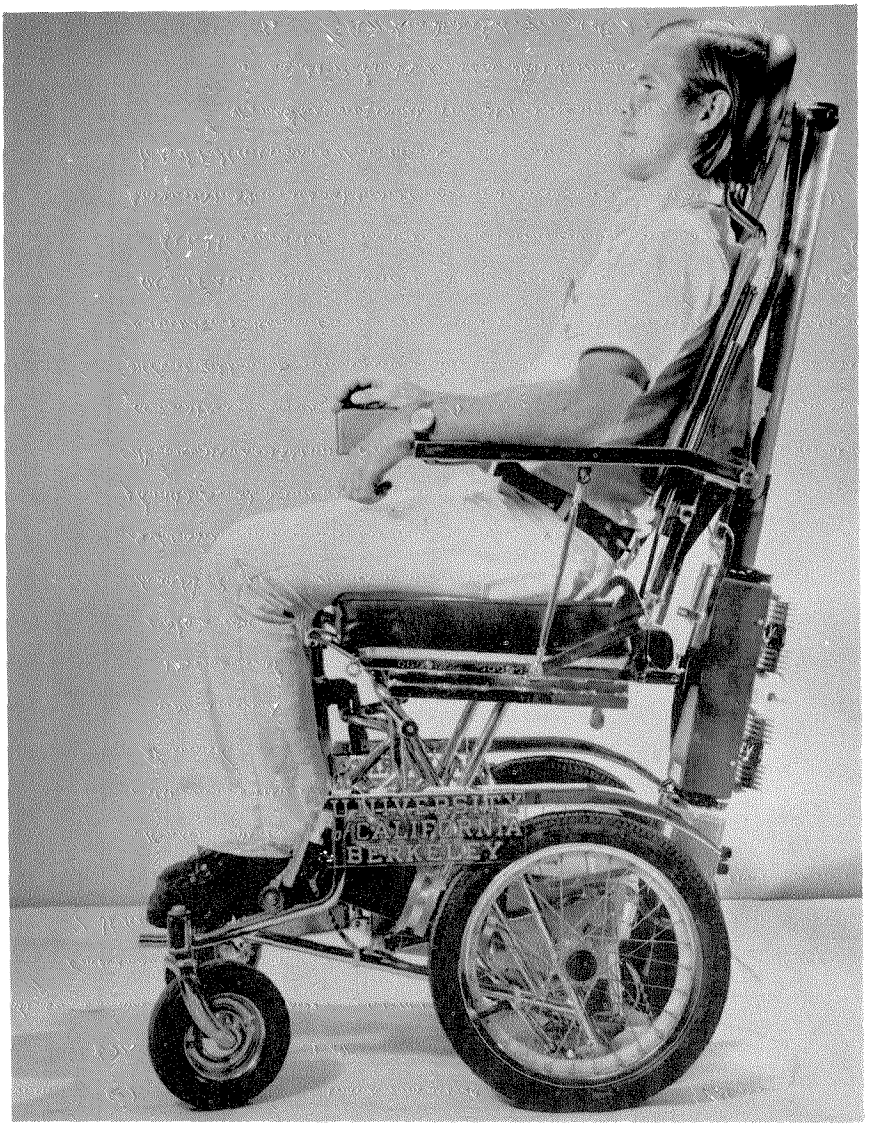

FIGURE 1.—UC wheelchair at maximum (27 in.) seat height with feet retracted.

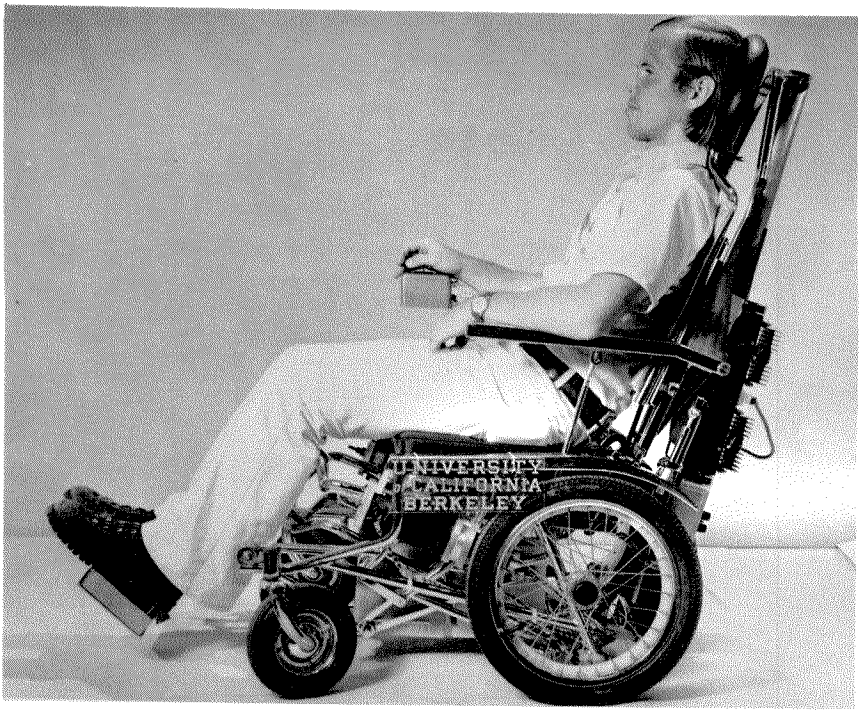

FIGURE 2.—Normal seat height, legs partially extended. Lateral transfer is unobstructed across rear wheel fender when swing-away armrest is up.

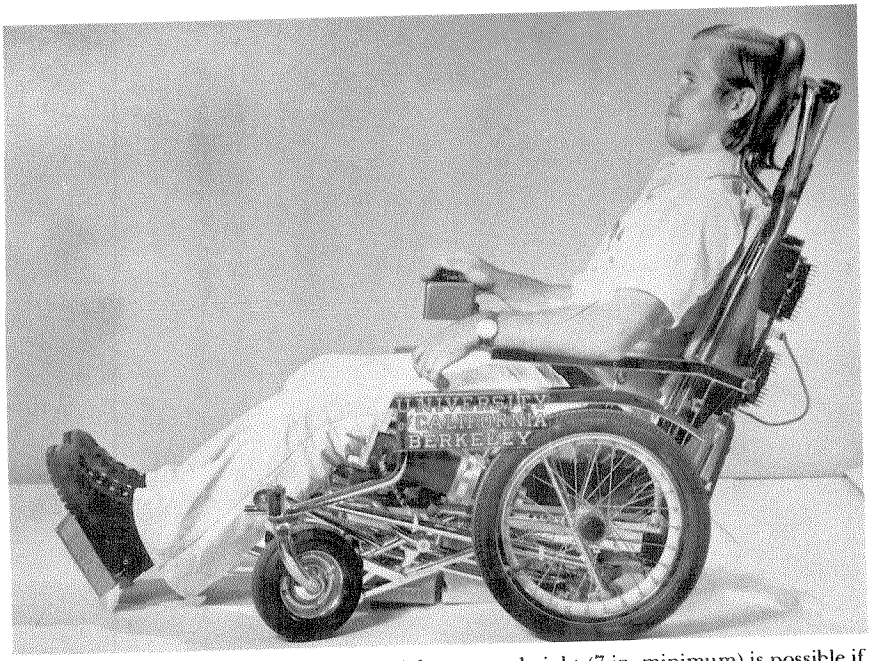
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FIGURE 3.—Lowest seat height (10 in.). A lower seat height (7 in. minimum) is possible if smaller batteries are used.

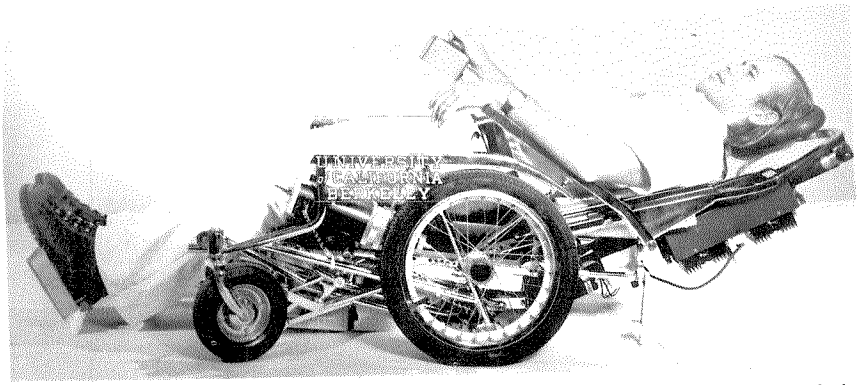
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FIGURE 4.—Continued shortening of the single actuator brings the backrest down with the seat and legs in the low (see Fig. 3) position.

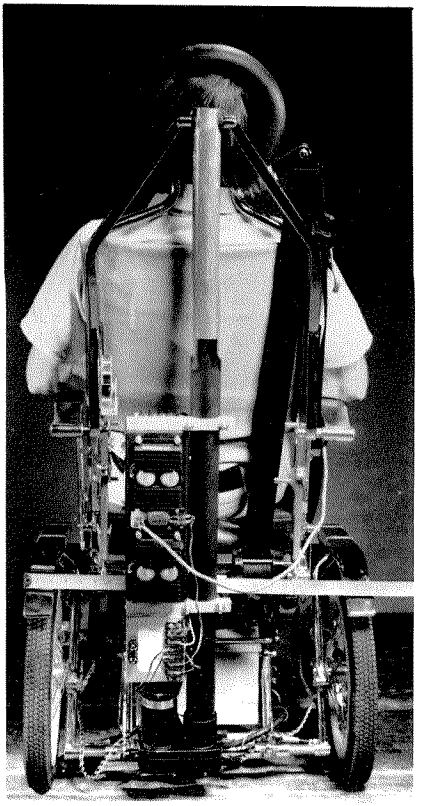

FIGURE 5.—When seat is at normal height (or lower) the overall width is 25 in. Note rear-mounted, central, single actuator, and attached speed control unit (for wheel motors).

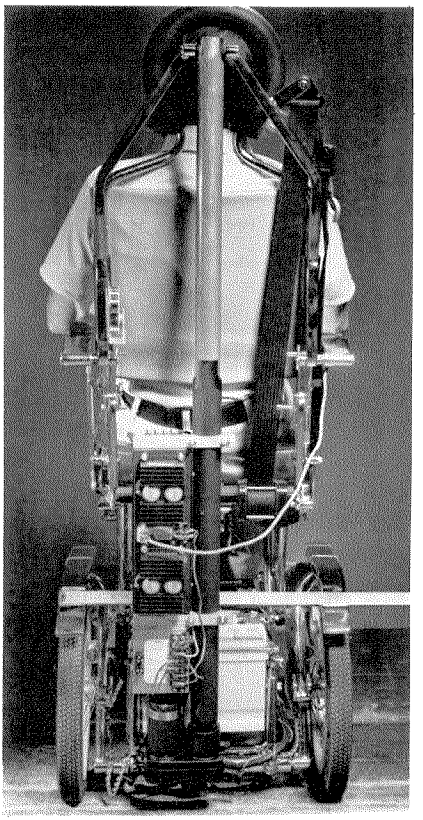

FIGURE 6.—As the seat goes up, the overall width reduces to 21 in. for easy entry through legal-sized toilet stall doors.

FIGURE 7.—Subject in UC wheelchair entering a Chevy van via a commercial tailgate lift.

FIGURE 8.—UC wheelchair in driving position in Chevy van. The seat is low, giving ample head clearance and visibility without wheel wells (subject height: 5 ft. 8 in.).

FIGURE 9.—Demonstration of head clearance, visibility, and driving controls access for a person of average height. The wheelchair seat will lower another 6 in. for a taller person.

2. *Height range:* A seat height range (Fig. 1-3) from 10 to 27 in. is possible and the ball-screw actuator automatically locks at any seat height — eliminating the need for a braking device. Limit switches control its range. The inclination of the lower seat surface stays continually at 7 deg. to the horizontal from maximum height to minimum height. The absolute minimum of the seat height (now 10 in.) could be reduced to 7 in. if the batteries were removed or replaced by more compact ones, such as the "dry" GEL-CELL types with an optimum configuration. Note that the wheelchair can be driven, with full castoring capability, at any seat height or with the back reclined.

3. *Obstruction-free transfer:* The most difficult part in designing the height-varying mechanism was to locate it entirely under the seat and beside the two auto batteries; the prime object being to keep the wheelchair compact and have no obstruction to lateral transfer in and out of the chair. There are no lateral obstructions for seat heights from 18 to 24 in.

4. *Speed:* The UC wheelchair carrying a 180 lb. person will climb a 6 percent grade at 3 m.p.h., using the two Ray motors and Motorette speed control unit. A steady level surface speed of 7 m.p.h. can be attained. Acceleration is quite adquate.

5. *Battery range and life:* These quantities have not been measured yet. Life and range should be as good as an E&J wheelchair with belt drive, Motorette with tire-friction drive, and Advanced with a chain drive, if, in each case two comparable auto batteries are used. Two large capacity golf-cart batteries will not fit. The wheelchair could be modified to accept a single golf-cart battery with the penalty that the lowest seat position would increase from 10 to 14 in.

6. *Maneuverability:* This feature is felt to be quite adequate, since the dimensions of the chair are minimal and it will turn about on its own axis. A 40-in.-wide hallway, or equivalent is sufficient space. Also, the Motorette unit gives smooth control and variable acceleration, which is essential for moving about quickly and positively in tight quarters.

7. *Stability:* It is a serious challenge to try and make the UC wheelchair dynamically stable when the seat is high, frame narrowed, and footrest pulled in. Anyone can produce a "wheelie" (front wheels leaving the floor) with the seat high at maximum acceleration (joy stick forward) from a standing start. Obviously, on a steep incline with the seat high, it would be easy to overturn the wheelchair. Since the wheelchair is very stable and safe with the seat low, an electronic device, which will limit acceleration and top speed as a function of seat height, will be added. No penalty in performance will be paid because the high seat position will only be used for reaching up high or maneuvering in tight spaces.

8. *Narrow passage:* The present prototype will pass through 25-in.-wide openings at all seat heights; at maximum seat height (or up to ½ in. lower) it will pass through a 21-in. opening, and turn around in a 40-in. hallway.

9. *Vertical mobility:* With the quadriplegic occupant strapped in or with one elbow looped through either side backrest handle, he will be able to reach the floor with one hand by leaning slightly to one side (Fig. 10). The maximum height reachable depends upon available arm function but it would be at least 9 in. higher than possible with a standard 18-in. seat height. Then wall telephones, light switches, above-sink shelves are accessible. In high position, the quadriplegic has the same head height as a 5-ft. person (Table 1), so he can be almost at eye level with a normal standing person for conversation, speech making, and sports; a great psychological boon. The chronic problem of adapting standard wheelchairs to varying desk, table, and bench heights (by armrest cut outs or complete removal) is met by the universality of vertical height adjustment. Finally, the quadriplegic can see out of windows and over surfaces inaccessible to him before.

10. *Frontal vertical surface access:* Since the footrest of the UC chair retracts in high-seat position to a point where the toes are behind the front of the fixed frame and castor wheels, it is possible to make a very close approach within 3 in. of the knees (Fig. 1) to a vertical surface. In

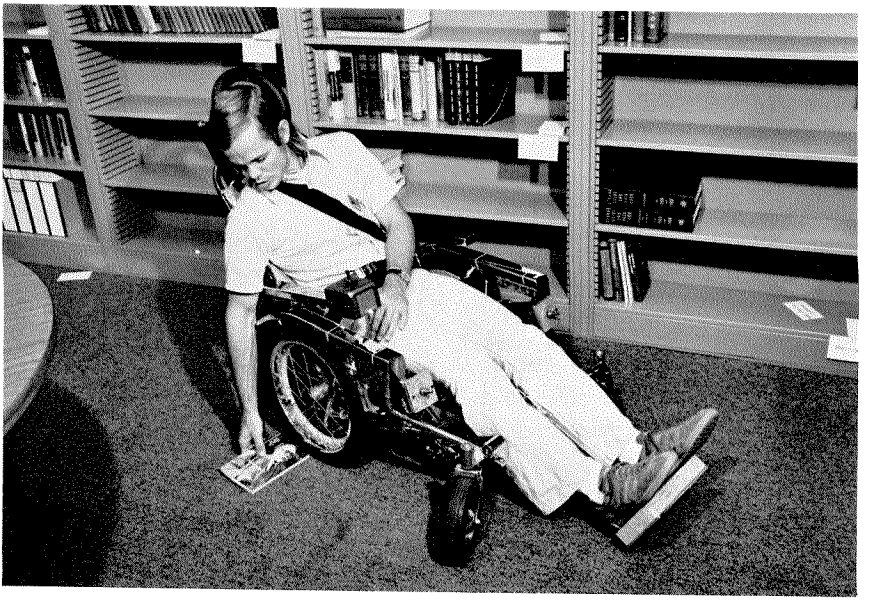

FIGURE 10.—A minimum of leaning is necessary for reaching objects on the floor with the seat low (Fig. 3 configuration).

conventional wheelchairs (or the UC chair in a lower seat position) every vertical surface must be approached tangentially from the side in order to reach it with the hands (arms extended).

11. *Reclining:* A no-cost feature of the UC chair is the full reclining of the backrest when the seat is low and legs extended. Not only will this be helpful in redistributing pressure on the buttocks, but also it allows resting while in the wheelchair and passage under 24-in. horizontal barriers. Unfortunately, reclining is not possible at other seat heights (e.g. for guerney-to-table-type transfer) but, again, no price was paid for the present reclining feature—continuous shortening of the actuator, with seat low, simply pulls the backrest down.

12. *Life expectancy:* Life tests on the UC wheelchair are yet to be carried out. Daily activities testing on three VA-funded prototypes will begin in late 1974. Long life is expected because redundancy in the linkage assembly has been completely avoided; ball or RULON bearings have been used in all moving pivots or sliders; parts have been sized to take a 50 percent overstress; and all frame members have been protected by chrome plating. The Berkeley prototype has been operated intermittently every day for several months, with many battery charges.

13. *Van compatibility:* It is possible for a 6-ft. person to enter, see out of, and drive a conventional van or Checker sedan while seated in the UC wheelchair. No modifications of the van are necessary except to cover

the step area next to the left front door and to provide access via a ramp or "tailgate" lift (compare dimensions in Tables 1 and 2). Even in the smallest (Dodge) van a 6-ft.-high man in the UC wheelchair in low position can enter either door with 3 in. of head clearance, sit inside with 9 in. of clearance, and drive with 8 in. of vertical eye clearance (eye distance below top of windshield). This means that either a 6-ft. 6-in. man would be accommodated or the 6-ft. man could move the seat up from 3 to 6 in. for better steering wheel reach, etc.

Of interest is the fact that an average (or slightly higher) height person in the UC chair down low can fit through the door of a standard Checker sedan or station wagon and sit comfortably inside at, say, driving position with acceptable visibility. Inclining the backrest slightly more would improve visibility. Having a floor height of from 7.5 to 12.5 in. less than the van's, expedites wheelchair entry.

Quadriplegics in standard wheelchairs seem to be opting for Chevy vans (Fig. 7–9), probably because all clearances are greater than in the other two (Table 2). We, having a less critical clearance limitation, would choose the Ford van because of its more accessible (lower) floor.

Parenthetically, the UC wheelchair was originally designed to fit in driving position in a standard-sized 1974 Dodge (Plymouth), Ford or Chevy, or bigger two-door sedan. Obviously, as suggested above, there would be a head clearance and visibility problem. Since the UC wheelchair seat will go down another 3 in. (to 7 in. off floor) with batteries removed or reshaped (e.g., use small Gel-Cell types), this will suffice, except for very tall people.

14. *Fitting the population:* The UC wheelchair seat system will adjust for the 5th through 95th percentile in body size. The modes of adjustment are:

a. length of thigh
b. height of elbow above seat
c. angle of armrest
d. body width
e. height of head above seat
f. pillow height (fore-aft headrest position)
g. headrest angle (against back of head)
h. angle of backrest from vertical

The chair is adjusted to a new user as follows (Fig. 11):

First, the backbrace (Fig. 11, item 6) is set at approximately the right angle by turning the turnbuckles (item 22). The seat is run to a height such that the shank of the footrest is vertical. The user is positioned on the seat such that his lower legs are also vertical. (The thigh length adjusting link mounting screws (item 46) must be removed to allow the backrest (item 7) to swing to the correct position). The backrest is positioned to support the user comfortably, and the link mounting screw

(item 46) is inserted and tightened in the most appropriate hole in the seat plate (item 4). Now the backbrace angle can be reset if necessary

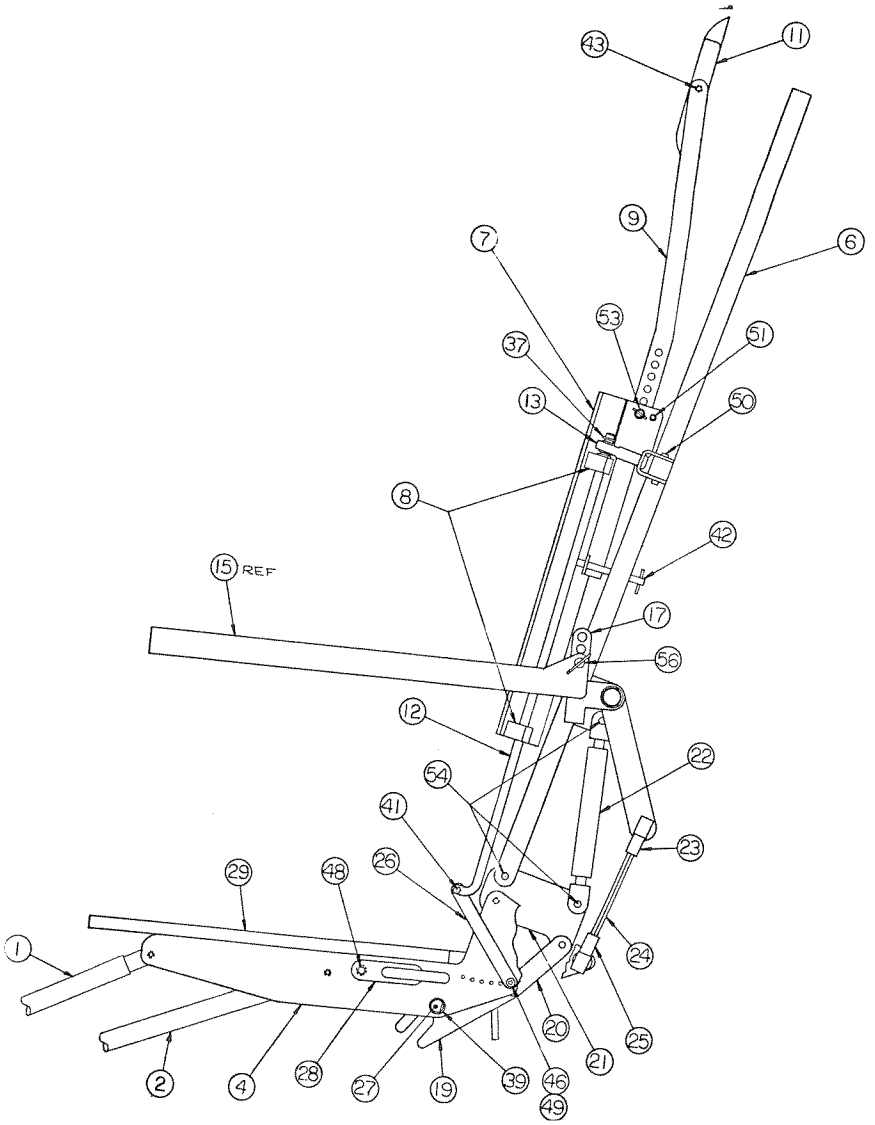

FIGURE 11.—Assembly drawing of the new seat, backbrace, pivot, and recline system.

Next, the armrest (item 15) is set at the correct height by removing the mounting pin (item 56), positioning the armrest, and reinserting the pin in the correct hole. For a person with a wide torso, the offset armrests can be switched side to side to allow an extra 2 in. of width. The armrest

angles can then be adjusted by rotating their respective turnbuckles (item 24).

Finally, the headrest must be positioned. First, the height is set by pulling the pins (item 53), moving the headrest to the desired position, then reinserting the pins. (Both sides must be done at once.) The "pillow height" is then set using the adjusting screw (item 42) at the bottom of each headrest support (item 9). Finally, the headrest angle is set by loosening the mounting screws (item 43), positioning the headrest, and retightening the screws.

15. *Daily activities performance:* Hopefully, the potential user of the wheelchair will be convinced by reading about functions 1 through 14 that this wheelchair will excel in daily activities use. Certainly the three quadriplegics who have briefly tried the UC wheelchair were enthusiastic. Further trial information will be available after the VA sponsors the construction and "field" testing (at VA Spinal Cord Injury Centers) of three prototypes during 1975. These tests will emphasize daily activities more than vehicle driving.

16. *A single wheelchair for everything but sleeping?:* Only time will tell whether a quadriplegic can do virtually everything while in only the UC wheelchair. It is well known that many severely handicapped persons have several wheelchairs: one for inside the home, one for outside, one for sports, one for airplane travel, etc. The practicability of a universal-function, powered wheelchair has yet to be tested.

17. *Wheels:* The 8 in. front castor wheels allow for reversing or sharp turning at all seat heights (e.g., at no time do they interfere with the mechanism or frame). Also, the 16 in. rear wheels are small enough to allow ample hand, forearm, and elbow freedom at all seat heights, as well as unobstructed transfer across the fender at normal chair height. The 1½ in. wide semi-pneumatic tires are adequate for the front casters. The 1¾ in. wide pneumatic rear tires are still better from a weight and cushioning standpoint. Wider tires would simply take up too much space.

18. *Actuators:* There is only one actuator for moving the mechanism. This single actuator: a. varies the seat height, b. retracts the leg rests, c. narrows the tread, and d. reclines the backrest. The Swedish Permobil has seven actuators. A disadvantage of having only one actuator is not being able to move each mechanism separately.

19. *Safety restraints:* A Volvo (aircraft type) inertia-reel, over-shoulder seat belt is provided to strap the quadriplegic securely to the wheelchair seat, yet give him freedom of arm motion (if he is capable of any). When he is a passenger in or driver of a van-type vehicle, the wheelchair seat will, in turn, be securely fastened to the floor of the van. Clamping will be done by the wheelchair elevating mechanism as follows: the wheelchair, with seat 2 in. above minimum height, moves forward until a locking pin

(Fig. 12) on each side of the backrest pivoting mechanism hits the vertical surface of a strong floor-mounted bracket. Lowering the seat height by 2 in. drops each locking pin into a bracket hole. Further seat lowering pivots the backrest forward 5 deg. and back again, rotates locking pin 35 deg. and lifts rear wheels ½ in. off the floor. Continued reclining of the seatback rotates locking pins still more—to a maximum of 100 deg. All the while, the wheelchair is restrained in all directions. Locking pin, wheelchair seat and occupant can withstand a 20 g frontal acceleration.

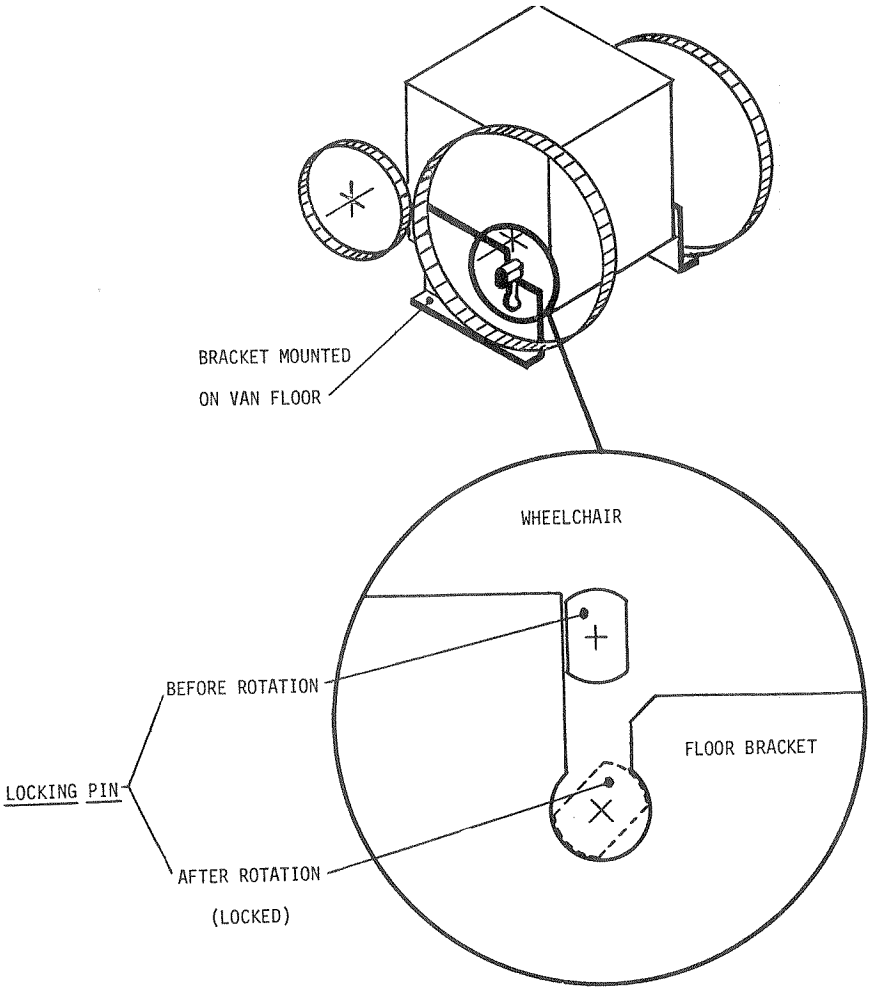

FIGURE 12.—Sketch of UC wheelchair van lock-down mechanism.

20. *Natural pivoting:* Traction, shearing, pulling, tearing, bunching, or shifting of clothing (or supporting skin) is prevented by the expedient of having the leg-extending mechanism "pivot" set at the anatomical knee joint and using a sliding backrest to accommodate a moving hip pivot. Note (Fig. 3 and 4) that reclining the backrest has shifted the head rest (and seat-back) 3 in. relative to the top of the actuator.
21. *Standardization:* Readily available materials and components are used as much as possible. For example, all frame chassis and mechanism parts are made of cold-rolled steel — mostly round and square tubing. The only heat-treated parts came that way, such as some machine screws, the transverse tube (lowest cross-member in Fig. 5), ball bearings in rod ends on links, wheels, motors, and actuator. The ball-screw actuator and motor is a standard (Saginaw) 24-in. stroke unit. Batteries are a standard VW (#2YW-111-645) and a Sears (#4310). The many ball bearings are stock items, the linear bearings are RULON (derivative of Teflon) sleeves. There are some exotic parts, such as the handmade nylon bevel gear (visible just inside the rear wheel rim in Fig. 1-4), and curved, tapered fenders.

DISCUSSION

Many compromises were necessary in the development of the UC PRAHN (powered, reclinable, adjustable-height, and narrowing) wheelchair. One such was the undesirable limitation on the lowest seat position caused by placing two lead-acid batteries under the seat (placing these batteries anywhere else would either make the wheelchair unacceptably large or top heavy). Another compromise was choosing a linkage which would limit the maximum seat height to 27 in. (another linkage might have provided greater height but would not lower the seat as much and would be bulkier or weaker). A third compromise was to reject the use of a linkage which would place seat-backrest "hip" pivot at the anatomical hip pivot (this would have precluded the van lock-down feature and also added greatly to the complexity). Instead, the sliding backrest expedient was used. A fourth "compromise" was to use swing-away, interchangeable arm rests, rather than detachable (or other type). This allows running the wiring for switches and joy stick through either armrest. There are several simplifying compromises where two or more functions were designed into one mechanism. The prime example is the use of a single actuator where four might have been used (if they would fit). The use of castor wheels and push-pull steering, along with the Motorette pulse-width-modulation unit, is a conventional compromise. Castor wheels must be damped to prevent shimmy and when they are deflected by a bump, rock, sidewalk edge, etc., it takes appreciable time to correct the wheelchair path with the joy stick control. Positive (like a

modified tiller type) steering is better and safer but more complicated and, hence, expensive. At this date, the new compact Motorette control unit is felt to be the best of those commercially available. A perhaps temporary compromise was to omit a battery charger, in the interest of simplicity and reduced weight. A small charger could be located in juxtaposition to the Motorette control box, e.g., just to the right of the actuator (see Fig. 5 and 6).

Many arbitrary "design" choices were made for the sake of expediency. The 3×16×16 in. plastic-covered foam cushion was selected on the basis that many quadriplegics use these. The backrest is an upholstered piece of curved sheet metal, similar to the plastic ones in manual folding wheelchairs. Basic research on cushions is being carried out at other places (13). The only restrictions on the design of the seat part of the UC wheelchair are that it articulate (for reclining) and that it be easy to transfer in and out laterally. This suggests a relatively flat seat (perhaps the armrests can supply the desired lateral support of a "bucket" seat). An electro-hydraulic actuator could have been used instead of the ball-screw unit, but the ram would have to have been double-acting (three telescoping, two concentric pistons moving out from one cylinder, sections). Also the ball-screw is completely self-locking, while the hydraulic one might not be, due to leaks which might even spill oil.

It was necessary for clearance purposes to use a central single-post support (Fig. 7) for the footrest. This concept seems to work very well. A fixed footrest appears to be adequate, but two inwardly folding ones could be substituted.

A more universally adjustable headrest has been developed.

Regardless of the number of expedient decisions, compromises, and "quickie" add-ons in the UC wheelchair, it is basically a useful device. It is a small package, very maneuverable and adequate in power, speed, and hill-climbing ability; it adds greatly to the "vertical mobility" of a quadriplegic; it goes through narrow bathroom or toilet stall doors and allows van driving or riding with good clearance and visibility; it has completely unobstructed lateral transfer capability; it is totally stable and safe with seat low under all speeds, acceleration, and inclination situations; it reclines for rest and pressure sore prevention; and its seat and occupant can be restrained for a 20 g frontal impact.

Not only does the UC wheelchair offer completely unobstructed lateral transfer, but the transfer also can be made in a downhill direction. The quadriplegic occupant simply raises the wheelchair seat to a slightly higher level than the, say, bed and moves (or rolls) over and down into the bed. For transfer from bed to chair, he sets the wheelchair seat lower than the bed.

A "wheelchair" may not be the best short-range mobility vehicle for severely handicapped people. But, given present understanding and

state of the art, it seems to be a good one. Wheels, although they in no way replace the myriad of leg functions, are excellent low speed, low friction, devices for transport on relatively smooth, level, to say, 10 percent grades. Three wheels are needed for stability, but four is a better number, as long as the frame or suspension system allows ground seeking (four wheel contact) at all times on warped surfaces. D.c. battery power is the expedient now since fuel cells are not operatioinal or too expensive; internal combustion engines are prohibited for use indoors. Pneumatic power is efficient (if a very high pressure air tank is used) but energizing high pressure tanks periodically is beyond the present state of the art.

CONCLUSIONS

The following sizes, characteristics, features, or functions have been built into the UC wheelchair, or will be by the time of this publication:

1. A 17-in. increase in vertical mobility or reach compared to a fixed-seat wheelchair.
2. A 21.0-in. wide by 39.5-in. long by 60.0-in. high (head of a 5-ft.-8-in. person) package with seat at a 27-in. height; a 24.5-in. wide by 58.3-in. long by 42.3-in. high package with seat at a 10-in. height; and a 24.5-in. wide by 54.5-in. long by 49.5-in. high package with seat at a normal 18-in. height.
3. A total unoccupied weight of 256 lbs.
4. A speed of 7 m.p.h. on the level and 3 m.p.h. on a 6 percent grade, carrying a 180 lb. person.
5. A turning diameter, between vertical walls, of 40 in., with seat at 27 in.; a 59-in. turning diameter with seat at 10 in. and backrest up.
6. A completely reclining back, with seat low.
7. Retracting footrest for close frontal approach.
8. Unobstructed lateral transfer provision.
9. Mechanical "pivots" at anatomical joints.
10. Adjustable to fit 90 percent of the population.
11. Two lead-acid automobile batteries.
12. Standard Motorette, joy stick pulse-width-modulation speed control unit for smooth, continuous speed variation.
13. Two drive motors.
14. Four mechanism functions carried out by a single actuator (Saginaw ball-screw).
15. Van driving or riding with wheelchair occupancy capability for a 6-ft.-6-in. person. Auto driving or riding could be accomplished for a 6-ft. person; a taller person would require special batteries (for lower seat height).
16. Excellence in the area of daily activities.

17. Protection in a frontal 20 g collision.
18. Anatomical joint and muscle therapy for knees and hips via the retracting leg rest — reclineable backrest feature.
19. Swing-away, adjustable armrests.
20. Positive gear drive.

CRITIQUE

The following shortcomings of the UC wheelchair are apparent:

1. It is expensive. The low bid for three prototypes was $4,100 each. This figure would be lower for a production model.
2. It is heavy (256 lb.).
3. The gears are noisy.
4. The elevating, narrowing, and reclining functions are not independent. However, this expedient greatly reduces complexity, size, and weight.
5. The 8-in. castor tires are heavy and hard.
6. Batteries are too high, heavy, and unshippable by aircraft (once activated with acid).
7. There is exposed grease on the male actuator sleeve cover.
8. Castor wheel, passive push-pull "steering" is a minimumly controlled, slowly-correctable scheme.
9. There are no parking brakes.

All other shortcomings of which the authors are aware will be corrected by the time of this printing (before the three test prototypes are built by Motorette).

PROPOSED FUTURE WORK (1975)
(In Order of Expediency — On a Funding Available Basis)

1. Reduce the noise level in the gears. The manufacturer may contribute here.
2. Add "parking" brakes—essential for transferring and hill safety.
3. Replace the lead-acid batteries with dry, rechargeable (say Gel-Cell types), smaller (or at least more flexible in terms of packaging), deep-charge batteries. This could increase the wheelchair cost slightly. Motorette and a battery manufacturer are developing a lead-acid battery with a coagulated gel (instead of liquid) acid. This is a nonspillable, partially-vented battery which can be taken on airplanes. At this time Motorette is only putting the gel in conventionally-shaped commercial batteries. Another fabricator, Gel Cell, makes individual 2-v. battery cells of various shapes which can be placed in other configurations and

orientations—giving great flexibility in shape of space and location on the wheelchair. These new gel batteries are more expensive than their predecessors and their ampere-hour capacity is lower by 40 percent, but they last longer. Space-saving considerations would make up for this loss in capacity, since more cells could be added in some nook or cranny around the wheelchair.

4. Add a speed and acceleration limiter which will be brought into play when the seat is high.

5. Eliminate the castoring system and replace it with a "programed," electrically controlled positive steering scheme.

6. Design a simple, unobtrusive van lift for the UC wheelchair.

7. Finish the auto lift for the UC wheelchair with some possible compromises:

a. enter the left front door, or

b. enter the right front door, but drive from the right front side using special hand controls or an "English" right hand driving setup.

8. Design a new variable-seat-height manual wheelchair for paraplegics, without batteries, motors, and actuator (but negator springs for counter-balancing). Greater compactness, height variation, and versatility would be possible.

9. Design another new powered wheelchair which will climb a 12-in. curb or into a van with a single half-floor-height step (32 in. × 32 in.), and fit into a standard U.S. two-door sedan.

10. Design a pulse-width-modulation control box without mechanical relays.

11. Add a two-speed gear changer for higher speed on the level and more efficient hill climbing.

PHILOSOPHY

Simply put, there are two basic approaches to improving the physical lot of severely handicapped people. The approach which has been used mostly to date is to adjust the physical world to fit the physically handicapped person in, say, a wheelchair. An example is the current endeavor of many concerned groups to eliminate architectural barriers, such as curbs, hard-to-open doors, steps, narrow bathroom or toilet doorways, and high wall telephones, switches, etc. To the last might be added the need to adopt special tables, desks, workbenches, wall cabinets, and bookshelves to the reach or clearance associated with conventional wheelchairs. Barriers might be eliminated just in a home and office or in a whole community or campus. The latter approach is very expensive, particularly if there are few wheelchair users in the community.

The other approach (attempted here) is to try to adapt the wheelchair itself to negotiate or accommodate as many "barriers" as possible. If the wheelchair seat can be elevated, or depressed to any reasonable height, the user can sit under almost any conventional table, desk, bench, etc. In some cases a 2-in. or less thick table top will fit under the armrest and over the legs (see Fig. 1). Vertical walls can easily be reached in front with the seat high (Fig. 1). Reclining the backrest enables passage under a 24-in. high horizontal barrier. The drive system operates for all configurations. Retracting footrests plus the narrowing capability (Fig. 5 and 6) provide for very good maneuverability in small spaces; a 22-in. toilet stall door can be negotiated or a van interior (Fig. 8 and 9). A curb-climbing mechanism can be added (in a forthcoming model) which will allow a 12-in. curb traverse or climb into a vehicle with a 12-in.-high floor or, in two stages, one with a 24-in-high floor.

Of course old architectural barriers, and potential ones in new structures, should be eliminated as often as possible. After all, anything which makes mobility easier for wheelchair-bound people makes life easier for other physically handicapped, diseased, or elderly people. But, again, this is only one important approach. Designing "wheelchairs" to overcome many types of barriers is another worthwhile approach.

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