

CLINICAL REPORT

Iterative design and evaluation of new prone carts for individuals with SCDs: A technical note

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Abstract—This paper summarizes a series of projects funded since 1992 to address the compelling need to improve the quality of life for persons with spinal cord dysfunctions who use prone carts. Specifically, Veterans Services Organization, National Institute on Disability and Rehabilitation Research (NIDRR), and the VA Rehabilitation Research and Development funded studies to develop new consumer-driven designs for prone carts. Using an iterative approach, this team of clinicians and designers (1) evaluated existing prone carts; (2) designed a new manual prone cart; (3) designed a new motorized prone cart, including a standing model; and (4) are collaborating with manufacturers to market and commercialize the new prone carts. Prototypes were developed at the Milwaukee Institute of Art and Design with the assistance of Ortho-Kinetics, Inc., and Everest & Jennings and were clinically evaluated at two Veterans Affairs Medical Centers (Tampa and Milwaukee) with patients and caregivers and for compliance with applicable ISO (International Organization for Standardization) for electric wheelchair standards.

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INTRODUCTION

A prone cart is a flat horizontal stretcher, propelled by a patient while lying in a prone position. Prone carts are used for mobility by individuals with spinal cord dysfunctions (SCDs) who cannot use a wheelchair because of the risk of aggravating existing pressure ulcers. Prone carts are typically used in Veterans Affairs (VA) spinal injury centers because they treat patients long term. Patients with SCD reported that prolonged use of a prone cart resulted in chronic neck, shoulder, and back pain. Additionally, existing prone carts lacked user accessible angle adjustability, chest-support area, as well as storage, eating, and working areas. Motorized prone carts are needed for patients who are unable to self-propel a manual cart because of limited arm and/or hand function, fatigue, or other medical conditions. Using a prone cart, patients are able to move around the spinal cord injury (SCI) unit or hospital grounds independently.

The original impetus for designing a new prone cart was given by Mr. Emil (Sammy) Schnurr, a Milwaukee VAMC patient with SCD and a double above-knee amputee who has "lived" on a prone cart for many years. Mr. Schnurr formulated the idea for a cart for which the body support would be angled up as opposed to being horizontal. The angled-up prone cart would help him look up without developing neck and shoulder pain, thus improving his quality of life and other's who use a prone cart. The first conceptual design for a new prone cart, a 1992 student project at the Milwaukee Institute of Art and Design, received the prestigious "Industrial Design Excellence Award," from the Industrial Designers Society of America (IDSA). Based on this initial work, the team designed new manual and motorized prone carts with sponsorship from Federal agencies and veterans service organizations.

Purpose of Prone Carts

Individuals with SCD use prone carts for mobility when pressure ulcers prevent them from sitting in a wheelchair. Persons with SCD are at high risk for developing pressure ulcers caused by decreased mobility, limited activity, impaired nutrition, incontinence, impaired circulation, sensory deficits, injury because of transfers, and multiple other factors. Because individuals with SCD sit in wheelchairs or lie in a supine position for extended time periods, the sacral and ischial areas are the most common sites for pressure ulcers (1,2). Once pressure ulcers develop, the patient must stay off affected areas until they are healed. The healing process can last several weeks to months and in some cases years. During this time, patients with ischial or sacral pressure ulcers must lie on their side or in a prone position, precluding the use of a wheelchair. Patients on extended bed rest are faced with boredom, isolation, dependence, and increased health risks. The prone cart provides a mechanism for mobility without jeopardizing the patient's treatment or healing process. With a prone cart, patients can independently move in the hospital or hospital grounds and independently perform activities of daily living (ADL). There are two versions of prone carts: manual (self-propelled) and motorized. Motorized prone carts are needed for patients who cannot use a manual cart because of limited arm and/or hand function, fatigue, or other medical conditions.

Commercial Availability and Use of Prone Carts

Currently, only two manual prone carts are commercially available in the United States. They are manufactured by Everest & Jennings® (E&J) and Gendron®, Inc. The new VA prone carts were designed to correct the problems associated with existing prone carts, specifically, to ease the chronic pain and discomfort associated with self-propelling while simultaneously holding up the upper torso necessary for adequate vision. The new VA prone carts feature an articulated torso support that elevates the user while propelling the cart. These prone carts also provide variation in postures and positions to aid in comfort, pressure relief, and completion of ADL.

Since the early 1990s, motorized prone carts have not been commercially available. While prone carts contribute significantly to the quality of life for persons with SCD, there is currently a limited number of patients with SCD who have sacral or ischial pressure ulcers and cannot use a manual cart because of limited arm and/or hand function, fatigue, or other medical conditions. The need for motorized prone carts is anticipated to increase as the number of persons with disabilities age and experience decreases in physical stamina or develop cardiac, respiratory, and other debilitating chronic illnesses.

To quantify manual and motorized prone cart use in SCDs, we sent a survey to 95 SCI centers in the United States. These SCI centers were randomly selected from the American Association of SCI nursing membership directory. The survey was directed to the nurse manager of the SCI center, since this person typically is responsible for both the inventory and purchase of equipment. Of the 35 SCI centers that responded, 54 percent (n = 19) represented VA facilities and 46 percent (n = 16) represented public or private facilities with SCI units. Findings indicated a need for both manual and motorized prone carts. The use of motorized prone carts had declined in recent years because of their unavailability (no current manufacturer). As existing motorized carts wear out, they cannot be replaced. However, as persons with SCDs age, stamina and muscle strength diminish, chronic illness develops, and secondary disabilities emerge. Many manual prone cart users of today may have the need for motorized prone carts in the near future. Clearly, VA medical centers (VAMCs) use prone carts more extensively than private or public facilities. Three of the nurse managers from private rehabilitation facilities surveyed had never seen a motorized prone cart. Use may be more prevalent in the VA because of a

combination of length of stay and unique patient populations served.

The VA has longer hospital stays; one can assume the demand to provide mobilization options increases the longer the patient is confined to bed. Additionally, VA SCI centers admit persons with SCDs for management of secondary disabilities, such as pressure ulcers, while public or private facilities are limited to acute rehabilitation.

Problems with Existing Manual Prone Carts

The design of prone carts has not changed for decades. Individuals with SCD who use a manual prone cart for mobility, either long or short term, have identified significant problems with current models (3). Specifically, prone carts interfere with socialization and provide inadequate body support and comfort, pose significant safety risks, and impede independence in completing ADL. Each of these critical problems is briefly discussed.

Interferes with socialization

Prone carts currently available are not adaptable enough to permit many activities that wheelchair users take for granted: working, shopping, doing household chores, and participating in many recreational or social activities. The flat surface of the cart interferes with the patient's ability to have direct eye contact with others. This social isolation can lead to loneliness, depression, and/or withdrawal.

Causes discomfort, pain, and fatigue

When the patient is using a prone cart, his or her prone position leads to severe discomfort. Specifically, the back and neck are hyperextended and undue pressure is exerted on the elbows. Hyperextension of the neck occurs when pillows are used to hold the head up for visibility necessary to propel and steer the cart. Patients complain of severe to moderate neck pain, resulting from hyperextension; moderate to severe pain in the back, shoulder, neck, and elbow areas; and fatigue.

Presents safety risks

Independent propulsion can be difficult when moving the cart over carpet or uneven terrain and when the wheels are wet. The carts are inadequately padded, creating the potential for additional skin breakdown, particularly on the knees, ankles, elbows, chin, foot, and pelvic area. No provisions are available either to prevent cath-

eter tubing from kinking, which can cause serious medical complications, or to protect the patient's feet hanging behind the prone cart. Tall or obese patients or patients with ostomies are now precluded from using the current models and unfortunately must be confined to bed while their pressure ulcers heal. The design of the wheels and brakes can present unnecessary safety risks for patients during transfer and transport. Independent propulsion is difficult over carpet or uneven terrain. Rear casters tend to get caught in elevators, sidewalk grooves, or other cracks. Motorized versions of the prone cart present special challenges related to visibility for steering, speed, and maneuverability.

Limits independence in ADL

Many of the simplest ADLs are either impossible or too difficult to sustain when patients are confined either long or short term on a prone cart. Patients find self-propelling difficult while carrying personal items or beverages. Additionally, the prone cart flat surface makes completion of many activities of daily living more difficult. See **Figure 1**.

METHODS

Before designing new prone carts, we evaluated existing models as part of a VA Rehabilitation Research and Development Service pilot study (3). From this evaluation, functional and performance criteria were established to develop new prone cart prototypes for clinical evaluation at the Milwaukee and Tampa VAMCs. Typical of many such projects, an iterative process of prototype development and clinical evaluation was used to develop the new prone carts. Whenever possible, design suggestions, observations, and responses received in the clinical evaluation from patients and caregivers were incorporated into the next prototype until the new design was completed and met the established performance goals and design criteria.

Safety and Performance Criteria

We designed the new prone carts with safety and performance criteria resulting from the evaluation of existing prone carts and with input from patients and caregivers.



Figure 1.
Typical existing prone cart.

Overall goals

New prone carts must be safe for patient use, must not contribute to upper torso pain and discomfort when self-propelling, must be adequately cushioned to support the body comfortably, and must promote independence in completing ADL.

Frame design

The new prone cart must be designed with an all-around “bumper-like” frame that protects the user and facilitates access by caregivers for treatment purposes.

Body support

The new prone cart body support must be contoured to prevent rolling over; it must have an angle adjustable torso portion and an arm-elbow support area.

Propulsion systems

The new prone carts must be available in a manual and in a powered version: a manual cart for paraplegics or other individuals capable of self-propelling and a powered version for tetraplegics and other individuals who cannot self-propel.

Adaptability to various patient sizes

The new prone carts must be available in several lengths to accommodate different sizes of patients.

ITERATIVE DEVELOPMENT OF NEW PRONE CARTS

The Sammy LS

The Sammy LS (**Figure 2**) is a prone cart that was designed based upon the angled body support idea of Mr. Emil (Sammy) Schnurr. This prone cart features:

- Carbon fiber structure.
- Height adjustable with hand-operated hydraulic levers.
- Angle-adjustable contoured body support composed of two sections: a torso support that adjusts from 0° to 40° upward and a rear section that adjusts down from 0° to 20°.
- A front deck with elbow support pads and a beverage holder.
- A side pullout storage drawer.
- Rear body support extensions with feet protector.

Dimensions

Length: 142 cm and 183 cm with rear extensions, height: 89 cm, wheel-to-wheel width: 65 cm, and wheel-base: 95 cm.

Propulsion

Manual propulsion with two composite 61.5-cm front wheels with pushrims and two 12.5-cm swivel rear casters.



Figure 2.
Sammy LS prone cart.

Evaluation

In addition to the first Sammy LS, which Mr. Schnurr has lived on since 1993, two other Sammy LSs, were used for several months at the Milwaukee and Tampa VAMCs. Based upon user feedback, the following assessment of the Sammy LS design was made. It is ideally suited for double amputees, children, or small individuals whose height is in the 5 to 25 percent percentile or measuring between 160 and 168 cm. Its wheelbase provides easy access to a van equipped with a wheelchair lift. See **Figures 3** and **4**.

The positive features are:

- Overall bold design and red color.
- Angle-adjustable torso support.
- Contoured body support.
- Elbow support pads.
- Front deck with beverage holder.
- Height ideally suited for access to public phone, tables, counter tops, beverage disposers, etc.
- The negative features are:
- The cart equipped with rear extensions was difficult to propel because of weight displacement toward the rear.
- When angled down, the body support gave users the sensation of sliding off.
- Access to the storage tray was difficult.



Figure 3.
New prone cart versus old.



Figure 4.
Sammy LS in use in a veteran's residence.

The criteria for the Sammy LS's redesign were to:

- Elongate the frame.
- Design the prone cart for fabrication with steel tubing.
- Use alternate means of raising or lowering the angle adjustable torso/leg support.
- Relocate the storage tray under the front deck.

SCI-PC 22 Prone Cart

Based upon the evaluation results of the Sammy LS, another prone cart named the SCI-PC 22 (**Figure 5**) was designed. Fabricated in 1994 in collaboration with



Figure 5.
SCI-PC 22 prone cart.

Ortho-Kinetics, Inc., it was constructed with a 2.5-cm square steel frame.

The SCI-PC 22 manual prone cart features are:

- Contoured angled adjustable torso and body support with 5-cm-thick Naugahyde vinyl-covered urethane foam cushioning.
- Torso support adjustment from 0° to 23° upward and body support adjusting downward from 0° to 20°.
- Padded front deck for elbow support, with a reading, eating, and drink holder area.
- Pullout front drawer.

Dimensions

Length: 178 cm, height: 79 cm, wheel-to-wheel width: 58.5 cm, and wheelbase: 104 cm.

Propulsion

Manual propulsion with two composite 61-cm front wheels with push rims and two 20-cm swivel rear casters.

Evaluation

The SCI-PC 22 was evaluated at the Milwaukee and Tampa VAMCs with several paraplegic and tetraplegic patients who were hospitalized for treatment of pressure ulcers and caregivers. The evaluation involved transferring from the hospital bed to the prone cart, ambulating and performing a series of ADL tasks. This evaluation found that the positive features of the prone cart are:

- Overall length.
- Height ideally suited for access to public phone, tables, and counter tops.
- Ease of self-propelling and mobility.
- Good weight distribution.
- Contoured body support.
- Articulated torso support.
- Padded front deck with the elbow support area and an eating, working, and drink-holder area.
- The negative features were found to be:
- When angled down, the rear portion of the body support gave users the sensation of sliding off the cart.
- Lack of a body-support removable section for urine and/or ostomy bags.

Criteria for redesign

Redesign for steel tubing fabrication and fixed leg support area to include a removable section for urine and/or ostomy bags.

Tubular Manual Prone Cart

The tubular manual prone cart (**Figure 6**) incorporates in its design the evaluation findings of the SCI-PC 22 (**Figure 7**). Two versions were designed to accommodate users' different body sizes. The short version is for use by individuals between the 5 and 50 percentile or measuring between 160 and 173 cm. The long version is to accommodate taller individuals between the 70 and 95 percentile or measuring between 175 and 185 cm.



Figure 6.
Tubular manual prone cart.



Figure 7.
Evaluation of tubular manual prone cart.

Body support system

The prone cart body support consists of three sections: the torso, the lower body, and the elbow support areas. The length of the body support is of 176 cm for the long version and of 148 cm for the short version.

Torso support. The torso support comprises a cushioned trapezoidal section hinged on the frame with a chin cutout. The torso support elevates the patient's chest in three positions only: horizontal, 13°, and 23°, while letting his or her elbows and forearms rest on the cushioned front deck. Angle adjustment is achieved by manually positioning a hinged support, located under the torso, into a slotted panel with three stops corresponding to the angle adjustment.

The dimensions of the torso support are 56 cm in width at the widest area and 31.75 cm at the narrowest and 50 cm in length.

Lower body-leg support. This section of the support system tapers toward the rear. The length of the long version is 126 cm and 98 cm for the short version. For both versions, the width is identical: 44.5 cm at the narrowest area and 56 cm at the widest. A slot for passage of the urine bag tubing is included in this portion of the body support. This will prevent the tubing from becoming compressed.

Elbow-forearm support. The elbow and forearm support is integrated in the front deck of the cart and is cushioned for comfort and safety.

Cushioning. The body support and the front deck is cushioned with urethane foam of 35-44 IFD (indentation force deflection) density and covered with Naugahyde vinyl. This foam density was found to provide the best pressure distribution among various types of foam evaluated with a pressure mapping system.

Frame

The frame is constructed of steel tubing 3.8 cm in diameter and is divided in two areas:

- The undercarriage structure, designed to receive the front wheels, rear casters, and a shelf for personal items.
- The upper horizontal frame, forming an all-around structure onto which is attached the body support and an under-deck pullout storage drawer. This horizontal frame acts as a bumper for protection of the cart's body support and the user's feet at the rear.

Frame dimensions and weight

- Long frame: Length: 203 cm, height: 76 cm, width: 75 cm, wheelbase: 106 cm, and weight: 40 kg.
- Short frame: Length: 178 cm, height: 76 cm, width: 75 cm, wheelbase: 106 cm, and weight: 37 kg.

Minimum turning radius

- Long frame: 175 cm.
- Short frame: 153.5 cm.

Static stability testing

The manual prone carts were tested for static stability with the method outlined for ISO (International Organization for Standardization) wheelchair standards: WC 01—Determination of static stability, for forward, rearward, and sideways tipping. Static stability was measured when the prone cart was positioned on a platform with a 75-kg subject (**Table 1**). The platform was tilted up or down slope, and tipping was achieved when the front or rear wheels of the prone carts lifted off the platform. The same procedure was repeated with a 100-kg subject (**Table 1**).

Frame finish

A high-resistance powder-coated red finish was used to make the new manual prone carts as attractive as possible compared to the chrome finish used on existing prone carts.

Propulsion

Manual propulsion with two composite 61-cm front wheels with VA patented 38-mm pushrims and two 20-cm swivel rear casters.

Motorized Prone Cart

The motorized prone cart (**Figure 8**) was designed for patients who cannot use a manual cart because of limited arm-hand function, fatigue, or other medical conditions.

Table 1.

Static stability test results of manual prone carts with two subjects, weighing 75 and 100 kg, respectively.

Static Tipping Angle	Subjects	
	(75 kg)	(100 kg)
Rearward	29°	29°
Forward	29°	29°
Sideward	24°	22°



Figure 8.
The motorized prone cart.

Two motorized prone carts were fabricated. A long frame cart for clinical evaluation at the Milwaukee and Tampa VAMCs and a short frame cart for testing with applicable ISO electric wheelchairs standards at the Pittsburgh VA Human Engineering Research Laboratory. We used ISO to test the prone cart to assess its structural integrity, stability, and safety.

Body support system

The motorized prone cart body support is identical to that of the manual prone cart.

Frame

The motorized prone cart frame is constructed of steel tubing 3.8 cm in diameter and is divided in two areas:

- The undercarriage structure was designed to receive two electric motors, a shelf for batteries, wheels, and rear casters
- The upper horizontal frame that forms an all-around structure onto which is attached the body support and an under front-deck pullout storage drawer. This horizontal frame acts as a bumper for protection of the cart's body support and the user's feet in the rear.

Frame dimensions and weight

- Long frame: Length: 203 cm, height: 76 cm, width: 78 cm, wheelbase: 106 cm, and weight: 83 kg.

- Short frame: Length 187 cm, height: 76 cm, width: 78 cm, wheelbase: 106 cm, and weight: 81 kg.

Frame finish

A high-resistance powder-coated red finish was used to make the new motorized prone cart as attractive as possible.

Drive system

The motorized prone carts are equipped with two 24-V electric power wheelchair motors, one for the right and the left. Each motor is connected to 31.75-cm front wheels. The electric motors incorporate a parking brake and a mechanism that disengages the clutch for manual pushing of the prone cart. Finally, the electric motors are coupled with a joystick controller unit and enable the user to propel the cart in forward and/or reverse mode, as well as turning and braking.

Power source

The motorized prone carts are equipped with two 12-V sealed gel-cell batteries, rated at 20 to 120-A hours. The batteries are enclosed in safety boxes and are located on an open shelf to facilitate access.

Wheels and casters

The motorized prone carts are equipped with two 31.75-cm front wheels and two 20-cm rear casters.

RESULTS AND DISCUSSION

The development of the manual and motorized prone carts involved an iterative process of prototype fabrication and clinical evaluation at the Milwaukee and Tampa VAMCs. Patients and caregivers were provided with questionnaires that addressed issues of their interactions with the motorized prone cart. The questions related to the user's body positioning on the cart, the physical characteristics of the cart, the cart's maneuverability and performance, and the user's access from the cart. Additionally, informal discussions and interviews with patients and caregivers as well as photography provided valuable information to the designers.

Clinical Evaluation Results of Manual Prone Cart

Four tubular manual prone carts were continuously used for 2 years and evaluated at the Milwaukee and Tampa VAMCs. Of the 12 patients who evaluated the manual prone cart over time, 67 percent were paraplegic and 33 percent were tetraplegic. Seventy eight percent reported complete injuries and twenty-two percent incomplete injuries. Respondents had been injured for an average of 13 years. All respondents were male between the ages of 24 and 60 years, with a median age of 42 years. Fifty percent responded that their physical profile was large, and fifty percent described themselves as medium or small. The majority (80 percent), reported to be right-handed. Each of these patients evaluated the manual prone cart with regard to body positioning, physical characteristics, cart maneuverability and performance, and access. Findings are briefly described in the following paragraphs.

Body positioning on cart

Ninety percent reported that the body support was long and wide enough. All reported that the front deck was neither too small nor too long, but 50 percent felt that it was not big enough for eating or writing. All reported that there was enough area for the elbows on the front deck, the cushioning was comfortable, and the drink holder was conveniently located and large enough. All reported that the drawer was conveniently located and of appropriate size. Eighty-five percent of the respondents found that the catheter opening suited their needs, was properly located, and did not cause pressure.

Physical characteristics of cart

Torso support. Of all respondents, 70 percent preferred to use the 23° angle position of the torso support, while 20 percent preferred the 13° angle position, and 10 percent the horizontal position. The majority reported ease of manual angle adjustment.

Brake location. Eighty percent responded that the brake location did not interfere when self-propelling the cart.

Dimensions of the cart. Seventy percent of all respondents indicated that the length and the height of the cart were just right for their needs.

Pushrims and type of wheels. All reported that the 38-mm pushrims were just right to self-propel. All reported that they could reach the pushrims easily,

and 60 percent reported that pneumatic tires were not difficult to use in indoor or outdoor settings.

Cart maneuverability and performance

All respondents reported to feel safe and secure on the cart; they also found that the cart crossed thresholds and ascended ramps easily. Seventy percent reported that it rolled in a straight line, 80 percent that it turned easily, and 75 percent that their arms did not rub against the side of the cart when propelling. All respondents rated access as “easy” from the cart to cabinets, counter tops, a water fountains, elevator control buttons, public telephones, cafeteria serving lines, vending machines, etc.

In summary, the new manual prone cart was deemed to be safer, more comfortable, and more conducive to independence than the other commercially available carts.

Clinical Evaluation Results of Motorized Prone Cart

For 1 year, 13 patients and 26 caregivers used and evaluated one motorized prone cart at the SCI Center of the Tampa VAMC. All 13 patient respondents were males between the ages of 26 and 65 years, with a mean age of 51.5 years. All patients described themselves as having a medium physical profile. The majority (80 percent) reported to be right-handed. Twenty percent were amputees or had another impairment, sixty percent were paraplegics, and twenty percent were tetraplegics. Of the patients with SCD, 70 percent reported complete and 30 percent incomplete injuries, and all were using prone carts because of pressure ulcers. The average injury of respondents occurred 17 years ago. Findings are briefly described in the following paragraphs.

Body positioning on cart

All respondents reported that the body support was long and wide enough and found it to be comfortable. All reported that the front deck was neither too small nor too long. However, 50 percent felt that the front deck may be too small on which to eat or write. (Note: the front deck was designed to facilitate access to a table to eat or write.) Both patients and caregivers reported that there was enough area for the elbows on the front deck and that the cushioning was comfortable. Both patients and caregivers reported that the drink holder was conveniently located (90 percent) and large enough (70 percent). They also found that the front pullout drawer was conveniently located and was of appropriate size. Finally, both patients

and caregivers reported that the catheter opening was properly located and did not cause pressure.

Physical characteristics of cart

Torso support angle. Both groups preferred to use the middle position 13° over both the high 23° position and the horizontal position. The majority reported difficulties using the manual angle adjustment.

Location of electronic controls. All patients reported that the location was convenient and allowed the motorized prone cart to be easily maneuvered.

Battery shelf location. Seventy-five percent of caregivers reported that it was conveniently located for access to the batteries.

Dimensions of cart. Both groups indicated that the length and the height of the cart were just right. All caregivers also found that the height of the cart was appropriate for treatment of patients.

Cart maneuverability and performance

Maneuverability. All patients reported that they felt safe on the cart; it rolled in a straight line and over concrete, tile, or carpet; it turned easily; and it crossed thresholds and ascended ramps easily.

Access from cart. All respondents generally rated the access as “easy” from the cart to cabinets, counter tops, water fountains, elevator control buttons, public telephones, cafeteria serving lines, vending machines, etc.

In summary, the newly designed motorized prone cart was deemed to be safe, comfortable, and conducive to independence. Since no commercially motorized prone

carts are currently available, patients and caregivers were enthusiastic about the mobility option this new cart provided and described the impact of this cart on quality of life.

Testing with ISO Standards

Of the two types of prone carts, manual and motorized, only the motorized prone cart was tested at the Pittsburgh VA Human Engineering Research Laboratory for compliance with applicable ISO electric wheelchair standards, since there are no specific standards for prone carts. The intent of testing was to assess the prone cart's structural integrity, its static and dynamic stability, efficiency of brakes, etc. Data from ISO testing are valuable to consumers and/or providers to help in selecting wheelchairs (4).

The following tests were performed on the motorized prone cart, and results are presented for each test in **Tables 2 to 8**:

- Determination of static stability (**Table 2**).
- Determination of dynamic stability (**Table 3**).
- Determination of efficiency of brakes (**Table 4**).
- Determination of energy consumption (**Table 5**).
- Determination of overall dimensions, mass, and turning space (**Table 6**).
- Static, impact, and fatigue strength tests (**Table 7**).
- Determination of the obstacle-climbing capability (**Table 8**).

Of all the tests performed, only the static, impact, and fatigue strength tests could not be completed, because of a rear-caster-stem weld failure. This led to incorporate gussets to strengthen the caster stem of new models.

Table 2.

Determination of static stability.

Stability Direction			Tipping Angle		
Orientation	Description	Test	Least Stable	Test	Most Stable
Forward	Front wheels locked	9.3	40°	9.5	N/A
	Front wheels unlocked	9.2	40°	9.4	N/A
Rear	Rear wheels locked	10.3	50°	10.5	N/A
	Rear wheels unlocked	10.2	50°	10.4	N/A
	Anti-tip devices*	11.2	N/A	11.3	N/A
Sideways	Left	12.1	22°	12.2	N/A
	Right	12.1	22°	12.2	N/A

*“Least Stable” and “Most Stable” refer to positioning of anti-tip devices.

Table 3.
Determination of dynamic stability of electric wheelchairs.

		Observed Dynamic Response	Score			
No tip		At least one uphill wheel remains on test plane.	4			
Transient tip		All uphill wheels lift then drop back onto test plane, and antitip devices do not contact test plane.	3			
Transient anti-tipper tip		All uphill wheels lift, then drop back onto test plane and one or more antitip devices contact test plane.	2			
Stuck on anti-tip device		All uphill wheels lift off, wheelchair anti device(s) contacts test plane, and wheelchair remains on the antitip device(s).	1			
Full tip		Wheelchair tips completely over with wheelchair coming to rest at least 90° from its original position (unless caught by a restraining device or testing personnel for test purposes).	0			

Orientation	Test	Description	0°	3°	6°	10°		
Rearward stability	8.2	Stability when starting forward on an uphill slope.	4	4	4	4		
	8.3	Stability when stopping after traveling forward on an uphill slope.	Release controller	4	4	4	4	
			Full reverse	4	4	4	4	
			Power off	4	4	4	4	
	8.4	Braking stability when traveling backwards.	Release controller	4	4	4	4	
			Full reverse	4	4	4	4	
			Power off	4	4	4	4	
	Forward stability	9.2	Braking stability when traveling forwards.	Release controller	4	4	4	4
				Full reverse	4	4	4	4
Power off				4	4	4	4	
9.3		Stability when traveling from a sloped surface to a level surface.	N/A	4	4	4		
Lateral stability	10.2	Stability when turning on a downhill slope.	N/A	4	4	4		
	10.3	Stability while turning in a circle on a level surface.	3070 mm	N/A	N/A	N/A		
	10.4	Stability when turning suddenly while traveling forward on a level surface.	4	N/A	N/A	N/A		

CONCLUSIONS

This series of development projects enabled the successful design of a new manual and a new motorized prone cart for persons with SCDs to use.

Collaboration with a Manufacturer

The design team first collaborated with Ortho-Kinetics, Inc., of Waukesha, Wisconsin, a durable medical equipment manufacturer, for the frame fabrication of all new prone cart prototypes. This collaboration resulted in

manufacturing six prone carts. Four were purchased by the Milwaukee VAMC, the Wisconsin Paralyzed Veterans of America, and the Medical College of Wisconsin, and two were used for the motorized prone carts.

Technology Transfer

When the prone carts clinical evaluation was completed and following Ortho-Kinetics' decision that it was no longer interested in the prone carts, we presented the evaluations to representatives of Invacare, the E&J Division of Graham-Field Health Products, Inc., and Gendron, Inc. Of these three companies, two were interested in

Table 4.

Test methods and requirements for the effectiveness of brakes.

Test Plane Inclination	Direction of Travel @ Maximum Speed	Minimum Braking Distance (mm)		
		Normal Operation	Reverse Command	Emergency Power Off
Horizontal	Forward	1,097	948	937
	Reverse	640	543	577
3°	Forward	1,143	967	747
	Reverse	660	547	620
6°	Forward	1,200	1,026	820
	Reverse	757	620	683
10°	Forward	1,473	1,073	907
	Reverse	1,183	1,207	1,403

Table 5.

Determination of energy consumption of electric wheelchairs and scooters theoretical range.

7	Test Method
7.11	Calculate theoretical range of wheelchair from formula: $R = \frac{C \times D}{E \times 1000}$ $R = \frac{34 \times 1090}{2.3 \times 1000}$ $R = 16.1 \text{ km}$ R = Theoretical range in kilometers C = Capacity of battery in ampere-hours at 5-hour rate of discharge as declared by battery manufacturer D = 20 times length of center line of test track expressed in meters E = Electrical charge ampere-hour used during test

the prone carts to replace their existing models: E&J-Graham-Field Health Products, Inc., and Gendron, Inc. A final decision has not been reached by a manufacturer to market the prone carts.

New design

During clinical evaluation, caregivers suggested that another version of the motorized prone cart be designed. This prone cart would include a body support that elevates patients vertically. With patients standing, several physiological parameters can be improved, including

Table 6.

Determination of overall dimensions, mass, and turning space.

Test	Measurements	Value
5.1.1	Overall length including leg support and footrest	1,870 mm
5.1.2	Overall length without leg support and footrest	N/A
5.1.3	Overall width	760 mm
5.1.4	Overall height with backrest in upright position	925 mm
5.2	Dimensions of folded wheelchair	N/A
5.2.1	Minimum folded length	N/A
5.2.2	Minimum folded width	N/A
5.2.3	Minimum folded height	N/A
5.2.4	Minimum folded volume	N/A
6	Mass	80.7 kg
7.1	Minimum turning radius	1,535 mm
7.2	Turn around between limiting walls	2,020 mm

improved bladder function, decreased calcium in the urine, increased bone density, decreased leg spasticity, decreased number of bed ulcers, and improved bowel function. No such prone cart is currently available commercially. With sponsorship from the VA Rehabilitation and Development Service and in collaboration E&J Division of Graham-Field Health Products, Inc., the design of motorized stand-up prone carts has been completed and clinical evaluation is under way.

Table 7.
Static, impact, and fatigue strengths.

Test	Static	Pass/Fail	
8.4	Armrest: resistance to downward forces	N/A	
8.5	Footrests: resistance to downward forces	N/A	
8.6	Tipping levers	N/A	
8.7	Handgrips	N/A	
8.8	Armrests: resistance to upward forces	N/A	
8.9	Footrests: resistance to upward forces	N/A	
8.10	Push handles: resistance to upward load	N/A	
Impact		Pass/Fail	
9.3	Backrest: resistance to impact	N/A	
9.4	Hand rim: resistance to impact	N/A	
9.5	Casters: resistance to impact	Pass	
9.6.3	Lateral impact	Pass	
9.6.4	Longitudinal impact	Pass	
9.7.2	Frontal impact	Pass	
9.7.3	Offset impact	Pass	
Fatigue		Cycles Completed	Pass/Fail
10.4	Two-drum test*	155,415/200,000	Fail
	Preliminary current measurement	Not Taken	N/A
10.5	Curb drop test	Not Done	N/A

*Unit was placed on two-drum tester. At 34,933 cycles, right motor failed and was replaced. Test continued until 145,070 cycles; at which time a tire failed. Tire was repaired and testing continued. At 155,415 cycles, left motor failed and the test was halted. Motors were both replaced and a new test was started. At 28,718 cycles, a caster failed. At this time, it was decided to end all fatigue testing.

Table 8.
Determination of obstacle-climbing capability of electric wheelchairs.

	No Run Up (mm)	0.5-m Run Up (mm)
Forward	40	60
Backward	20	40

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