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Power wheelchair range testing and energy consumption during fatigue testing

Rory A. Cooper, PhD; David P. VanSickle, MS; Steven J. Albright, BS; Ken J. Stewart, BS; Margaret Flannery, BS; Rick N. Robertson, PhD

Human Engineering Research Laboratories, Highland Drive VA Medical Center, Pittsburgh, PA 15206; Departments of Rehabilitation Science and Technology, Mechanical Engineering, Medicine and Bioengineering Program, School of Health and Rehabilitation Sciences, University of Pittsburgh, Pittsburgh, PA 15261; Department of Biomedical Engineering, School of Engineering and Computer Science, California State University, Sacramento, CA 95819-6019

Abstract—The range of a power wheelchair depends on many factors including: battery type, battery state, wheelchair/rider weight, terrain, the efficiency of the drive train, and driving behavior. The purpose of this study was to evaluate the feasibility of three methods of estimating power wheelchair range. Another significant purpose was to compare the current draw on pavement to current draw on an International Standards Organization (ISO) Double Drum tester at one m/sec. Tests were performed on seven different power wheelchairs unloaded, and loaded with an ISO 100 kg test dummy. Each chair was configured according to the manufacturer's specifications, and tires were properly inflated. Experienced test technicians were used for the tennis court tests, and treadmill tests. An ISO 100 kg test dummy was used for the ISO Double Drum test. Energy consumption was measured over a distance of 1500 m for each of the three test conditions. The rolling surface was level in all cases. Repeated measure analysis of variance (ANOVA) revealed a significant difference ($p = 0.0001$) between the predicted range at maximum speed for the three tests. Post hoc analysis demonstrated a significant difference ($p < 0.01$) in estimated range at maximum speed between the Double Drum test and the treadmill test, as well as between the Double Drum test and the tennis court test. Our results indicate no significant difference ($p > 0.05$) between the predicted range at maximal speed between the treadmill and tennis court tests. A simple relationship does not exist between the results of range testing with the Double Drum tester and the tennis court. An alternative would be to permit the use of a treadmill for range testing as simple relationships between all pertinent treadmill and tennis court range data were found. For the Double Drum tester used, the current demand is higher than under normal usage. This presents a problem as current is related to load torque in a power wheelchair. Hence, the Double Drum tester friction must be reduced. The predicted range for the tennis court test at maximum speed ranges from a low of 23.6 km to a high of 57.7 km. The range of the power wheelchair can be improved by the use of wet lead acid batteries in place of gel lead acid batteries.

Key words: *batteries, fatigue testing, range, standards, wheelchair.*

INTRODUCTION

The range of a power wheelchair depends on many factors including: battery type, battery state, wheelchair/rider weight, terrain, the efficiency of

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Dr. Cooper, Mr. VanSickle, and Mr. Albright are with the Highland Drive VAMC and University of Pittsburgh, Pittsburgh, PA; Messrs. Stewart and Robertson and Ms. Flannery are with California State University, Sacremento, CA.

Address all correspondence and requests for reprints to: Rory A. Cooper, PhD, Director, Human Engineering Research Laboratory, VA Medical Center, Highland Drive, Bldg. 4, Rm. 058E, Pittsburgh, PA 15206.

the drive train, and the driving behavior of the user (1–6). Various wheelchairs have different ranges. This variation in range may be related to the intended purpose of the power wheelchair or the settings selected by the user (7). Batteries are rated in ampere hours (amp-hrs). The amp-hr rating and the current drawn by the power wheelchair will, to a large extent, determine the range. Range is an important metric in power wheelchair selection and design.

The range of a power wheelchair provides an estimate of the total distance that the wheelchair can be driven on a new, fully charged, set of batteries. This estimate may vary depending upon terrain and driving/maintenance habits (8). Determination of energy consumption for electric wheelchair standards that require use of large external areas (e.g., parking lots, tennis courts) may be prohibitive for some test laboratories that do not have access to tennis courts due to expense, parking lots because of space limitations, and/or weather that precludes working outdoors (WG1/620).

Kauzlarich et al. (8), examined battery performance of electric wheelchairs during indoor and outdoor conditions. Driving cycles were used to bench test various types of batteries. A single instrumented wheelchair was used for all tests. The indoor test consisted of a 0.241 km test track including numerous obstacles and floor surfaces. The wheelchair was driven continuously over the course for 11.1 km (3.85 hrs) until the battery was depleted. The outdoor test route covered 2.75 km per lap which included grades up to 4°. A paved footpath and parking lot were used for this test. The wheelchair was driven for 15.6 km (2.74 hrs) when the battery became depleted.

Fatigue testing is an important component of wheelchair standards testing. The ISO Double Drum tester plays a pivotal role in fatigue testing of power wheelchairs. During Double Drum testing, the power wheelchair can drive the rollers or the rollers can be used to drive the power wheelchair while in neutral. Many power wheelchairs are designed to be driven only short distances (i.e., a few hundred meters) while in neutral. This has lead to some power wheelchair drive and disengagement mechanisms being destroyed during Double Drum testing. This type of failure does not commonly occur in field use. Some test laboratories have interpreted the standard to imply that the wheelchair was to drive the rollers with the joystick set for one m/sec. However, not all Double Drum testers are alike. The friction of one Double Drum tester may vary significantly from another. It is also likely that the friction seen by the wheelchair while driving the Double Drum tester will be different from that when driving over a common cement walkway. In order for tests of power wheelchairs to be comparable, the current draw while driving the rollers of a Double Drum tester must be similar to that of a common driving surface (i.e., a cement walkway).

In response to concerns regarding range test and Double Drum test methods, we developed a set of experiments to determine if relationships exist between energy consumption at maximal speed on an ISO Double Drum tester, a motor driven treadmill, and while circumventing a tennis court (as proposed in the current ISO draft range test standard). The current draw at one m/sec was also recorded for each of the three test apparatus. Comparisons between results from the different methods were made using regression and ANOVA with repeated measures.

METHODS

Tests were performed on seven different power wheelchairs unloaded, and loaded with an ISO 100-kg test dummy. A specially designed circuit was used to measure battery voltage and load current (**Figure 1**), which was interfaced to Motorola MC6811-based analog-to-digital computer interface attached to the serial port of a computer. Data were collected at 20 Hz per channel on a DOS compatible 486 computer for the Double Drum and treadmill tests. A DOS compatible 8088-based laptop computer was used for the tennis court tests. Current and voltage were monitored at the battery terminals. Each wheelchair was tested on a Double Drum tester, treadmill, and tennis court. The slats were removed from the Double Drum tester prior to the experiment. New batteries were installed in each power wheelchair prior to testing, and all batteries were fully charged (as determined from open circuit voltage and charging current) before each experiment.

The state of charge for a new battery is somewhat subjective. Typically new batteries do not reach their full capacity until 30/40 charge/discharge

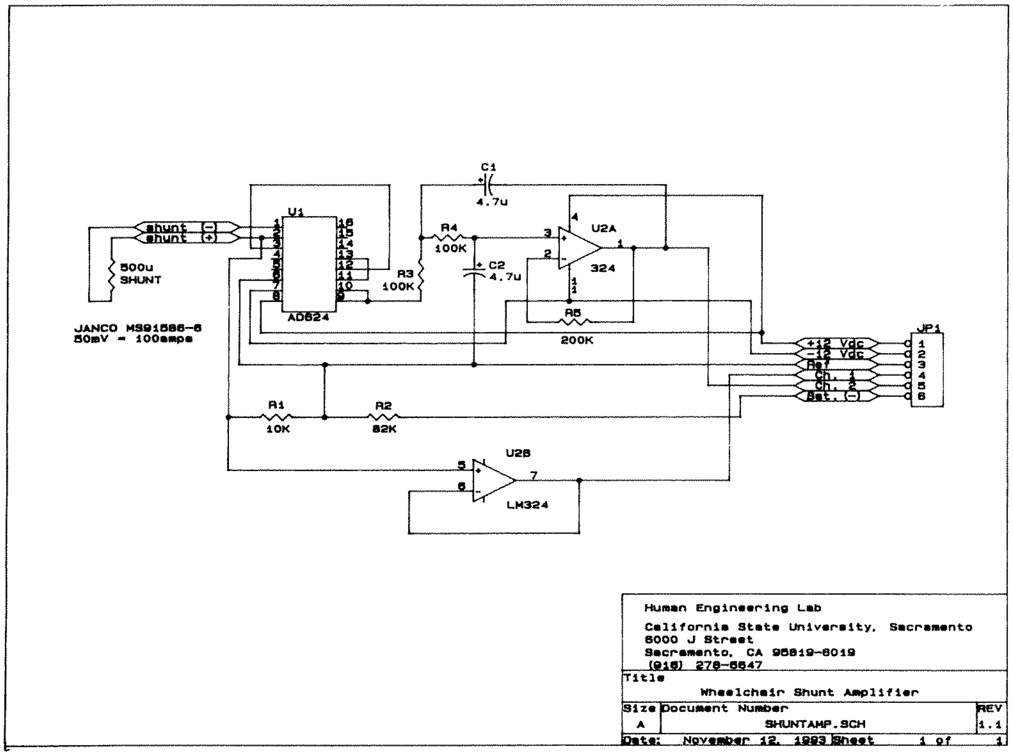

Figure 1.
Energy consumption computer interface circuit.

cycles. This can add variability in range when driving to discharge. However, each wheelchair was driven only 2250 m per test, which is well within the capacity of the battery. Thus, variations in state of charge will have minimal effect on the range estimates. In actual driving situations, range will be less than the idealized estimates of range determined with these methods. These methods are valuable for comparison purposes. The capacity (amp-hr) rating for batteries of the same size may vary considerably. For the purposes of these experiments and the draft ISO Range Test Standard (ISO-7176-04), the capacity reported by the battery manufacturer is used. Each wheelchair had its own batteries for this study. The short distance actually driven should minimize the variability. Furthermore, ISO and ANSI/RESNA range tests will be conducted in test laboratories around the world with various wheelchairs and batteries. One of the ISO and ANSI/RESNA objectives is to have tests of similar wheelchairs yield consistent results at each laboratory.

Each chair was configured according to the manufacturer's specifications, and tires were properly inflated (9–14). Experienced test pilots (technicians) were used for the tennis court tests and treadmill tests. An ISO 100-kg test dummy was used for the ISO Double Drum test (**Figure 2**). Each power wheelchair was used to drive front and rear drums with the Double Drum tester motor disconnected. The front roller is driven through a tooth belt drive. The dummy was seated properly in the chair as per ISO 7176-07. The types of chairs and their battery type are given in **Table 1** (15,16). All of the power wheelchairs tested used either inductive or resistive joysticks and switching servo-amplifiers with power MOSFET bridges.

Energy consumption was measured over a distance of 1500 m for each of the three test conditions (**Figure 1**). The rolling surface was level in all cases. The direction of motion remained constant on the Double Drum tester; whereas, with the proposed ISO standard tennis court range test, direction of rotation (i.e., direction was changed from clockwise to counter clockwise) was changed at 750 m. Wheelchairs were always driven in the forward direction. Each wheelchair was warmed up

Journal of Rehabilitation Research and Development Vol. 32 No. 3 1995

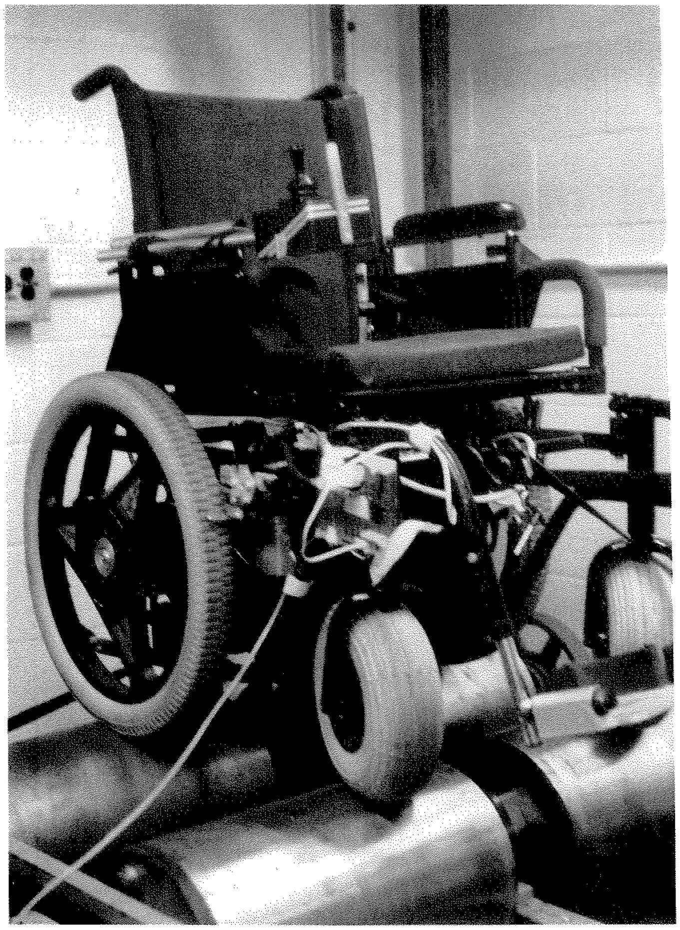

Figure 2.
Experimental set-up for Double Drum testing.

for 750 m at or near maximal speed prior to data collection to minimize the variation in current associated with heating electrical and electromechanical components. Hence, each wheelchair was driven a distance of 2250 m for each load case. Care was taken during treadmill testing to gradually increase the speed of the wheelchair and treadmill in synchrony. Each chair performed a no-load 1500-m range test, and a 100-kg load range test. A test technician walked/jogged alongside each chair providing guidance during the no-load tests for the tennis court. For the treadmill and Double Drum tester, a simple aluminum bracket was made to hold the joystick in the proper position, and a technician insured proper operation of the chair. The time required to complete the 1500 m was recorded and later used to calculate maximum speed of each wheelchair while performing each experiment. Distance was measured to the nearest revolution on the Double Drum tester by using both an optical encoder interfaced to a DOS compatible 8088-based computer and a mechanical counter which counted each revolution of the driven drum. Distance was measured on the treadmill using a mechanical counter which measured the distance traveled by the treadmill's belt in feet. For the tennis court test, a course was laid out around the perimeter of the tennis court, and the distance measured with a steel tape. The pilot was instructed to follow the course as closely as possible.

The 1 m/sec current draw was measured using the same methods as for the range tests. Three wheelchairs were tested on the Double Drum tester; whereas, seven were tested using a treadmill and a tennis court. Speed was adjusted by turning the speed potentiometer to a 1 m/sec maximum speed as measured over a known distance. For wheelchairs without a speed adjusting potentiometer, an experienced technician drove the wheelchair while carefully controlling the joystick position. In each case, the wheelchair was timed over a distance of 25 m. Several trials were made until the speed was consistently within ± 5 percent of 1 m/sec. Once the desired speed was achieved, current data were collected for 10 secs using the circuit described in **Figure 1**. All data were collected using a 100 kg load.

ANALYSIS

The raw data were converted to voltages (V) and amperes (amp), as appropriate. A program was written in Matlab which used 20 point smoothing prior to calculating current, voltage, and power. Power was calculated as the instantaneous product of current and voltage. This is valid as the current and power were measured in phase. Using the same program, energy was calculated by integrating power (using Simpson's Rule) from the time the test was started until the power wheelchair completed 1500 m. Range was estimated to be the product of the nominal battery capacity and the speed traveled, divided by the amps consumed (Equation 1).

$$range = \frac{nominal\ battery\ capacity \times speed\ traveled}{amperes\ consumed} \qquad [1]$$

Correlation analysis was used to determine the existence of linear relationships between current,

Table 1.
Description of power wheelchairs tested.

Make & Model	Battery Size	Battery Type	Amp•hour rating	System voltage
E&J Premier with 21st Century power components	Group 24	Wet Cell* Gel Cell	85 amp • hour 70 amp • hour	24 volts dc
E&J Tempest	Group U1	Wet Cell* Gel Cell	48 amp • hour 32 amp • hour	24 volts dc
E&J Marathon	Group 24	Wet Cell* Gel Cell	85 amp • hour 70 amp • hour	24 volts dc
Quickie P100	Group 22NF	Wet Cell Gel Cell*	55 amp • hour 48 amp • hour	24 volts dc
Quickie P110	Group 22NF	Wet Cell Gel Cell*	55 amp • hour 48 amp • hour	24 volts dc
Quickie P300	Group 24	Wet Cell* Gel Cell	85 amp • hour 70 amp • hour	24 volts dc
E&J Scooter Premier 3-Wheeler	Group U1	Wet Cell Gel Cell*	48 amp • hour 32 amp • hour	24 volts dc

All wheelchairs used deep cycle lead acid batteries, * indicates type of battery used during testing.

voltage, power, energy, and range for the three test conditions. ANOVA with repeated measures was used to examine differences between test methods (i.e., Double Drum, treadmill, and tennis court).

RESULTS

The data obtained from range testing on a Double Drum tester, treadmill, and tennis court with and without load are presented in **Table 2**. The mean current and power for the wheelchairs when loaded ($I = 13.3$ amps, $P = 325$ Watts) were higher than those when unloaded ($I = 10.3$ amps, $P = 261$ Watts). The results indicate that there is an increase in current ($p = 0.447$) and power ($p = 0.543$) with the 100 kg load added; however, they were not statistically significant. This apparent insensitivity to loading is likely a result of the variability in current and power among the different wheelchairs and their components (e.g., motors, drive-trains, tires, wheel types/sizes, total mass, and controllers), which creates a large standard deviation requiring higher differences between the means (loaded and unloaded) to attain significance. Repeated measures ANOVA showed that there were no significant differences between voltage ($p = 0.725$), current ($p = 0.725$), and power ($p = 0.628$) for the three experimental conditions. There were significant differences between the maximum speed ($p = 0.0008$) and energy ($p = 0.0109$) among the three experimental conditions. Post hoc tests showed the energy consumption for the Double Drum tests were significantly different ($p \leq 0.05$) from the energy consumption for the treadmill and tennis court tests. There were no statistically significant differences between energy consumption among the treadmill and tennis court tests. Post hoc tests also revealed a statistically significant difference ($p \leq 0.05$) between the maximum speed for the Double Drum and treadmill, as well as between the treadmill and tennis court.

Correlation analysis revealed a statistically significant linear relationship between treadmill and tennis court current ($r = 0.802$, $p = 0.0006$), power ($r = 0.896$, $p = 0.0001$), and energy ($r = 0.831$,

Journal of Rehabilitation Research and Development Vol. 32 No. 3 1995

Table 2.
Range test mean values of each test for the three experiments.

	Double Drum				Treadmill				Tennis Court			
	amps	watts	kJ	m/s	amps	watts	kJ	m/s	amps	watts	kJ	m/s
No Load												
Ch.1	10.3	255	195	2.7	30.9	761	355	3.2	33.3	824	446	2.8
Ch.2	9.2	230	223	1.7	10.7	267	212	1.9	2.4	57	45	1.7
Ch.3	9.9	233	233	1.8	6.2	144	101	2.1	5.7	138	111	1.9
Ch.4	10.0	249	220	1.7	4.4	109	90	1.8	4.8	118	97	1.8
Ch.5	11.2	278	278	2.3	12.8	500	254	2.9	10.5	260	136	3.0
Ch.6	14.5	349	227	2.4	6.7	162	91	2.7	7.1	179	108	2.6
Ch.7					4.3	106	75	2.1	0.3	8	7.5	2.2
100 kg												
Ch.1	12.6	307	307	2.4	27.6	692	345	3.0	19.1	466	304	2.3
Ch.2	12.7	288	288	1.5	8.9	222	187	1.8	6.6	155	139	1.7
Ch.3	12.8	297	297	1.7	8.3	195	144	2.0	8.8	198	126	1.8
Ch.4	13.3	310	284	1.6	8.8	195	185	1.6	8.4	205	184	1.7
Ch.5	22.6	553	552	1.6	22.5	607	332	2.7	19.8	545	327	2.5
Ch.6	16.3	390	253	2.4	10.7	252	143	2.6	12.2	301	200	2.3
Ch.7					7.3	175	137	1.9	6.0	146	101	2.0

amps = current in amperes, watts = power in watts, kJ = energy in kilojoules, m/s = average speed in meters per second.

p = 0.0002) at maximum speed (Equation 2). The person-product correlation is given by ‘r,’ and the probability that the linear relation is due to chance is given by ‘p.’ Treadmill speed and tennis court speed were also significantly correlated with one another (r = 0.908, p = 0.0001).

$$\begin{aligned} I_{TC} &= 0.78\ I_{TM} + 2.62 && \textit{amperes} \\ P_{TC} &= 1.08 P_{TM} + 81.42 && \textit{watts} \\ E_{TC} &= 1.01 E_{TM} - 24748 && \textit{joules} \\ v_{TC} &= 0.75 v_{TM} + 0.42 && m/s \end{aligned} \qquad [2]$$

The maximum speed on the Double Drum tester was statistically significantly correlated with treadmill (r = 0.839, p = 0.0006) and tennis court (r = 0.779, p = 0.0029) maximum speed. This is probably a manifestation of the digital speed control used by most of the power wheelchairs in this test group.

Current was measured for each power wheelchair while traveling at or near 1 m/sec (**Table 3**). This speed is representative of a brisk walking pace. ISO and ANSI fatigue tests on the Double Drum test machine are performed at 1 m/sec. For power wheelchairs, this machine can be used to test the robustness of the electrical system as well as the durability of the frame and components. Typically, the drums of the test machine are driven by the power wheelchair. If the load current of the power wheelchair varies significantly from that of normal use, the electrical system may fail prematurely. Our results indicate that the current required to drive the rollers of the Double Drum tester is statistically significantly higher ($p < 0.05$) than it is to drive the wheelchair on a treadmill or around a tennis court. Correlation analysis revealed that the 1 m/sec current for the Double Drum (r = 0.789, p = 0.4213), and treadmill (r = 0.71, p = 0.0737) were not significantly related to the tennis court current. The 1 m/sec current for the Double Drum tester and treadmill were significantly correlated (r = 0.999, p = 0.0108).

The range of each chair was estimated using the measured data and Equation 1. The 1 m/sec range data are susceptible to greater variability because data were collected for only 10 seconds during steady-state (**Table 4**). Wet cell batteries provide longer range of operation than gel cell batteries in every instance. This is because the amp-hr rating of a wet cell battery is consistently higher than that of a gel cell battery of the same size (16,17,18).

Table 3.
One meter per second test data.

	Double-Drum		Treadmill		Tennis Court	
	Speed	Current	Speed	Current	Speed	Current
Chair 1	1.02	11.25	1.00	28.0	0.93	5.45
Chair 2	1.02	9.4	1.00	7.3	0.98	2.21
Chair 3	1.02	9.4	1.00	7.7	1.00	4.22
Chair 4			1.00	6.3	0.98	3.63
Chair 5			1.00	19.7	1.03	3.77
Chair 6			1.00	3.1	1.12	3.75
Chair 7			1.00	1.0	1.00	2.85

All tests were conducted with 100 kilogram load, speed is in m/s, and current in amperes.

Table 4.
Estimated range with 100 kilogram load at maximum speed and at approximately one meter per second. (Units are in kilometers)

	Double-Drum		Treadmill		Tennis Court	
	1 m/s	Full Speed	1 m/s	Full Speed	1 m/s	Full Speed
Gel Cells						
Chair 1	22.8	30.3	9.0	27.4	43.0	30.3
Chair 2	18.8	20.4	23.7	34.9	76.6	44.5
Chair 3	12.5	15.3	15.0	27.8	27.3	23.6
Chair 4		20.8	27.6	31.4	46.7	35.0
Chair 5		17.8	12.8	30.2	68.8	31.8
Chair 6		37.1	80.5	61.2	75.3	47.5
Chair 7			11.5	30.0	40.4	38.4
Wet Cells						
Chair 1	27.7	36.8	10.9	33.3	52.2	36.8
Chair 2	21.5	23.4	27.2	40.0	87.8	51.0
Chair 3	18.8	23.0	22.5	41.7	41.0	35.4
Chair 4		23.8	31.6	36.0	53.5	40.1
Chair 5		21.6	15.5	36.7	83.5	38.6
Chair 6		45.1	97.8	74.3	91.4	57.7
Chair 7			17.3	45.0	60.6	57.6

$$R_{TC\max} = 0.57 R_{TM\max} + 18.32 \quad \textit{kilometers} \qquad [3]$$
$$R_{TCM\max} = 0.65 R_{DD\max} + 22.41 \quad \textit{kilometers}$$
$$R_{TC1m/s} = 0.40 R_{TM1m/s} + 48.94 \quad \textit{kilometers}$$

Repeated measure ANOVA revealed a significant difference ($p = 0.0001$) between the predicted range at maximum speed for the three tests. Post hoc analysis demonstrated a significant difference ($p < 0.01$) in estimated range at maximum speed between the Double Drum test and the treadmill test, as well as between the Double Drum test and the tennis court test. Our results indicate no significant difference ($p \geq 0.05$) between the predicted range at maximal speed between the treadmill and tennis court tests.

Regression analysis revealed a significant correlation between the predicted maximal range between the treadmill ($r = 0.756$, $p = 0.0018$) and tennis court tests, as well as between the Double Drum ($r = 0.614$, $p = 0.0336$) and tennis court tests. The predicted range at 1 m/sec were also significantly correlated between the treadmill and tennis court tests ($r = 0.536$, $p = 0.0481$).

Repeated measure ANOVA showed a significant difference ($p = 0.0029$) between the predicted range at 1 m/sec for the three tests. Post hoc analysis revealed that both the results of the Double Drum and treadmill tests were significantly different ($p < 0.05$) from the tennis court test. The analysis also showed no significant difference between the predicted range at 1 m/sec for the Double Drum and treadmill tests.

DISCUSSION

The range testing of power wheelchairs is a very important component of the ISO and ANSI/RESNA wheelchair standards. However, the use of a tennis court presents some problems for test facilities. Indoor tennis courts are often operated by private clubs or organizations who do not care to have their tennis courts used to test power wheelchairs. Some test laboratories are located in regions that frequently have inclement weather during some months of the year, which prohibits testing outdoors. Other facilities, such as parking garages, or sports gymnasiums, also may be suitable for testing. However, in most cases, these facilities are not associated with the test center. In addition, testing outside the laboratory requires specialized portable equipment which may not be readily available for the use of the test center.

All complete wheelchair laboratories are required to have a Double Drum tester for fatigue-testing manual and powered wheelchairs. This would be a convenient tool for range testing as well, but our results indicate that a simple relationship does not exist between the results of range testing with the Double Drum tester and tennis court testing. An alternative to the current ISO draft standard and ANSI/RESNA Standard, would be to permit the use of a treadmill for range testing as simple relationships between all pertinent treadmill and tennis court range data were found. The equations presented in this paper represent a possible means to relate treadmill and tennis court range tests. Some power wheelchairs will likely vary from these results, and this presents a potential problem when comparing results from different laboratories using varying test methods. At maximum speed, this should not present too great a problem as analysis of variance showed no significant difference.

Fatigue testing is also a very important component of power wheelchair testing. Unlike manual wheelchairs, whose wheels are driven by an external motor while being tested on a Double Drum tester, power wheelchairs must drive the drums with their internal motors. This permits the Double Drum tester to be used to evaluate the durability of the frame and components, as well as to assess the robustness of the electrical system. A persistent problem has been that the current used by the power wheelchair while turning the drums of the Double Drum tester may be substantially different from the current seen by the power wheelchair under normal circumstances. Our results indicate that, for the Double Drum tester used, the current demand is higher than under normal usage. This presents a problem as current is related to load torque in a power wheelchair. Therefore, the load torque must be reduced. This may be accomplished by increasing the diameter of the drums, effectively reducing rolling friction, reducing the friction of the bearings, and improving the efficiency of the coupling between the front and rear drums. Another method would be to leave the Double Drum motor coupled to the test apparatus, and use it to reduce the torque required by the power wheelchair. This last method requires the use of a closed-loop feedback control system to achieve reliable results.

The results in **Tables 2** and **3** show variability among wheelchairs and between tests. This is to be expected, since the wheelchairs include a variety of drive components (e.g., motors, drive-trains, tires, wheel types/sizes, total mass, and controllers). Some of the wheelchairs used open-loop control, whereas others used closed-loop speed control. Closed-loop speed controllers are designed to maintain constant speed regardless of surface friction or slope and can produce higher torque than open-loop controllers. The wheelchairs in the study used direct helical gear trains, worm-gear drives, or belts and pulleys. These drive trains have different efficiencies, and in the case of the treadmill, some can receive energy from the treadmill, whereas others can not. These factors all contribute to the results of this study, and to the wheelchair's actual driving behavior. The predicted range for the tennis court test at maximum speed ranges from a low of 23.6 km to a high of 57.7 km. The range of the power wheelchair can be improved by the use of wet lead acid batteries in place of gel lead acid batteries. However, wet batteries often require greater maintenance, and care during transport. No alternative batteries were tested (19,20). All of the manufacturers specified lead acid batteries for their wheelchairs. The range at 1 m/sec was typically greater than it was at maximum speed. This information may be useful to consumers; a low battery warning could extend their range by reducing the speed. Current draw on an incline will be greater than the values indicated in this paper. Some wheelchairs incorporate regenerative braking which allows some of the energy expended while going up an incline to be regained through charging the batteries while driving down an incline. Range will also vary with driving habits. An interesting result of this study is the finding that the tennis court test has an excess of 40 turns which require the pilot to slow the chair and than accelerate out of the turn. Yet all values recorded during the treadmill test, which is always straight at constant speed, were correlated with the tennis court results.

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