Department of Veterans Affairs

JRRD Journal of Rehabilitation Research & Development

Volume 45, Number 9, 2008
Pages 1251–1268

Evaluation of titanium ultralight manual wheelchairs using ANSI/RESNA standards

Hsin-yi Liu, BS;[1–2] Rory A. Cooper, PhD;[1–3]* Jonathan Pearlman, PhD;[1–2] Rosemarie Cooper, MPT, ATP;[1–2] Samuel Connor, BS[1]
[1]*Human Engineering Research Laboratories, Department of Veterans Affairs (VA) Rehabilitation Research and Development Service, VA Pittsburgh Healthcare System, Pittsburgh, PA; Departments of* [2]*Rehabilitation Sciences & Technology and* [3]*Bioengineering and Physical Medicine & Rehabilitation, University of Pittsburgh, Pittsburgh, PA*

Abstract—Comfortable propulsion and support, light weight, and small dimensions are important features that help preserve upper-limb integrity of manual wheelchair users and improve accessibility. The titanium wheelchair is a product developed in response to these goals, but none of the test results of titanium wheelchairs had been disclosed before this study was performed. We hypothesized that these titanium wheelchairs would be in compliance with American National Standards Institute (ANSI)/Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) standards. We tested 12 ultralight titanium rigid-frame wheelchairs (4 models) using ANSI/RESNA testing procedures and compared the test results with previously tested ultralight and lightweight aluminum wheelchairs. All wheelchairs passed the forward braking effectiveness test, but eight wheelchairs tipped backward before inclining to 7° in the rearward braking effectiveness test. All wheelchairs passed the impact strength tests, but six wheelchairs failed in the static strength tests. Three wheelchairs successfully completed the fatigue tests, but the remaining wheelchairs failed prematurely. This group of titanium wheelchairs had less equivalent cycles and value than the ultralight aluminum wheelchairs that were tested in a previous study. The failure modes revealed important design issues of each model. Our results suggest that manufacturers may need to perform more careful analyses before commercializing new products.

Key words: ANSI/RESNA, durability, failure, fatigue tests, lightweight, reference standards, rehabilitation, titanium wheelchair, ultralight wheelchair, wheelchair.

INTRODUCTION

Choice of a suitable wheelchair requires serious consideration. The U.S. Food and Drug Administration recommends testing wheelchairs using American National Standards Institute (ANSI)/Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) testing standards [1] to assess performance and safety and estimate life expectancy of a wheelchair. Results from ANSI/RESNA standard tests are a source of information about technical quality and performance and allow comparison of results across devices. The content of the standard tests covers many aspects that affect wheelchair usage and selection, such as dimensions, static stability, braking effectiveness, strength, and durability.

Abbreviations: ADA = Americans with Disabilities Act, ANSI = American National Standards Institute, CDT = curb-drop test, DDT = double-drum test, EC = equivalent cycle, ISO = International Organization for Standardization, RESNA = Rehabilitation Engineering and Assistive Technology Society of North America.

***Address all correspondence to Rory A. Cooper, PhD; Human Engineering Research Laboratories, 151R-1HD, VA Pittsburgh Healthcare System, 7180 Highland Dr, Pittsburgh, PA 15206; 412-954-5287; fax: 412-954-5340. Email: rcooper@pitt.edu**

DOI:10.1682/JRRD.2007.12.0204

Dimensions, weight, and turning radius clue consumers in to whether a wheelchair will fit in their homes, working environments, and transportation means. Wheelchair performance in the static stability tests reveals the estimated behavior of the wheelchair on an incline. The results indicate how the stability of the wheelchair is affected by adjustment of the axle and other components. Determining wheelchair strength and durability from retail advertisements and user manuals is difficult. Although medical insurers' prescription guidelines typically require 3 to 5 years before a replacement wheelchair will be covered, previous research has shown that the predicted life expectancy of some wheelchairs is significantly less [2–7]. Premature wheelchair failure could potentially injure the users and may require them to pay for replacements, which can cost several thousand dollars. According to Smith et al., wheelchair users expect wheelchairs to improve their quality of life and help them maintain or achieve a desired level of mobility [8]. Users expect their wheelchairs to be comfortable, easy to propel, safe, and attractive [8]. In a survey of wheelchair users with amyotrophic lateral sclerosis, the most desirable features of manual wheelchairs were a lightweight frame and a small turning radius [9]. Comfortable propulsion and support, light weight, and small dimensions are very important features, especially for active manual wheelchair users [10–11]. A lighter wheelchair has lower rolling resistance, which reduces the force required to propel it. Thus, lighter wheelchairs are suggested for preserving upper-limb function of manual wheelchair users [12]. Developing a lighter and more functional wheelchair is a goal for the design of many manual wheelchairs. The titanium wheelchair is a product in response to this goal.

ANSI/RESNA standard tests provide specific testing protocols to evaluate the performance and durability of wheelchairs and serve as a universal platform for data collection and comparison. Reports using ANSI/RESNA standards evaluated aluminum ultralight and steel lightweight wheelchairs. Ultralight wheelchairs lasted more than five times as long as lightweight wheelchairs before failures occurred during fatigue tests [2–3]. However, ultralight wheelchairs experienced more repairable component failures, such as bolt or caster-stem failures and screws loosening. Although repairable component failures do not damage frame integrity, multiple component failures require frequent maintenance and may place the user in hazardous situations.

Many ultralight wheelchairs have titanium frames and/or components. Since titanium has a higher strength-to-weight ratio than aluminum, if engineered correctly, it could preserve the strength of the wheelchair frame while lowering the weight. Conventional wisdom in our wheelchair clinic has been that people who use titanium chairs benefit from their highly durable and lightweight properties, although no standards testing results of titanium wheelchairs have been reported in the literature. Our goal in this study, similar to prior works in this area, was to test a series of commercially available titanium rigid-frame wheelchairs using ANSI/RESNA testing procedures. The standard test to determine braking effectiveness according to the International Organization for Standardization (ISO) was also incorporated in this study [13], since no braking effectiveness test for manual wheelchairs is included in the current version of the ANSI/RESNA standards. We hypothesized that these titanium wheelchairs would be in compliance with ANSI/RESNA standards and that they would be more durable than previously tested aluminum ultralight and lightweight wheelchairs.

METHODS

Study Wheelchairs

Twelve titanium rigid-frame wheelchairs representing four models from three manufacturers were tested using ANSI/RESNA wheelchair standard tests: the Invacare Top End (Invacare; Elyria, Ohio), the Invacare A4, the Quickie Ti (Sunrise Medical; Longmont, Colorado), and the TiLite ZRA (TiLite; Kennewick, Washington) (**Figure 1**). They were the most popular titanium ultralight rigid-frame wheelchairs prescribed at the Center for Assistive Technology at the University of Pittsburgh Medical Center. They were ordered with the same seat dimension specifications and standard components. Because of the cost and time to test wheelchairs, we only tested three wheelchairs of each model.

Standards Testing Procedure

We completed the whole battery of ANSI/RESNA manual wheelchair standard tests and assessed braking effectiveness using the ISO standard test. This article focuses on the test results of static stability; braking effectiveness; and static, impact, and fatigue strength tests.

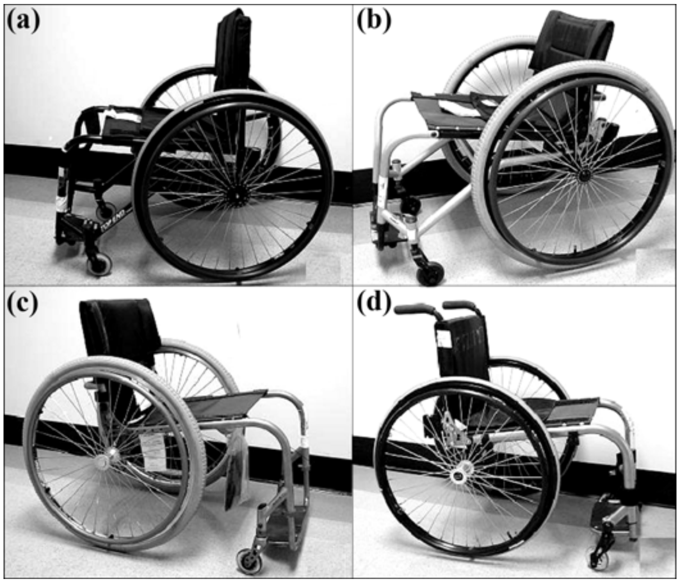

Figure 1.
Four models of titanium ultralight wheelchairs in this study: **(a)** Invacare Top End, **(b)** Invacare A4, **(c)** Quickie Ti, and **(d)** TiLite ZRA.

The dummy used in this study was built according to the requirements of ANSI/RESNA standards.

Static Stability

The wheelchairs were tested in their most and least stable configurations (forward and rearward directions) in the static stability tests (§1 in the ANSI/RESNA wheelchair standards). A 100 kg dummy was loaded into the test wheelchair. The wheelchair was secured on a platform using straps that did not interfere with tipping movement. An engineer increased the platform angle slowly and recorded the angle at which the front casters lifted from the platform just enough for a piece of paper to pass between the casters and platform. In the rearward stability tests, the rear wheels were locked with parking brakes or by securing the wheels with straps that limited the rolling motion of the wheels relative to the frame. In the other portions of the static stability tests, blocks or brackets that did not impede the rolling motion of the wheels were used to stop the wheelchair from rolling downhill.

We placed the wheelchair in its least stable position in the rearward direction by moving the rear-wheel axle forward, reclining the backrest backward, and increasing the front seat height by adjusting the caster position. We positioned the wheelchair in the extreme least stable position, since no indication or limitation for the range of the rear-wheel axle position was noted on the wheelchairs or in the user manuals. Most of the wheelchairs in their least stable setting tipped backward on a horizontal plane with the dummy loaded. Although these extremely unstable positions in the rearward direction were not realistic wheelchair settings, we still proceeded and recorded the tests because the purpose of having the standardized tests is to reveal the actual properties of the wheelchair. To address this limitation, we modified the testing procedure by placing the wheelchair facing downhill on the platform and securing it with straps to prevent it from tipping over completely (**Figure 2(a)**). The slope was then increased, and the angle at which the front casters touched the platform was recorded (**Figure 2(b)**). The reading was a negative number.

Braking Effectiveness

In the braking effectiveness tests (§3 in the ISO wheelchair standards), we kept the wheelchairs in the same setting as when they came out of the box (the axle was in the most rearward setting), loaded them with a 100 kg dummy, and engaged the rear brakes. The tests were performed on the same platform as the static stability tests. While increasing the slope of the platform, we recorded the angle at which the wheelchair started to slide downhill. The wheelchair was tested in its forward and rearward orientations. Since the steepest slope that fulfills the requirement of the Americans with Disabilities Act (ADA) is 7° (1:8), with a maximum rise of 75 mm (3 in.) for existing buildings and facilities, we expected the wheelchair to be able to stay stationary on a 7° slope.

Static, Impact, and Fatigue Strength Tests (Durability Testing)

Static, impact, and fatigue strength tests (§8 in the ANSI/RESNA wheelchair standards) evaluate the strength of the wheelchair structure by applying different types of loads on specific components. A pneumatic ram was used to apply static force to the footrest, armrests, and tipping levers (if present) according to the standard. Impact force was applied using a pendulum on several components of the wheelchair (footrest, caster wheels, pushrim) that are prone to impacting objects. Any permanent deformation or component failure was considered a failure as denoted in the standards.

Fatigue strength was evaluated by the double-drum and curb-drop tests (DDT and CDT, respectively). Each

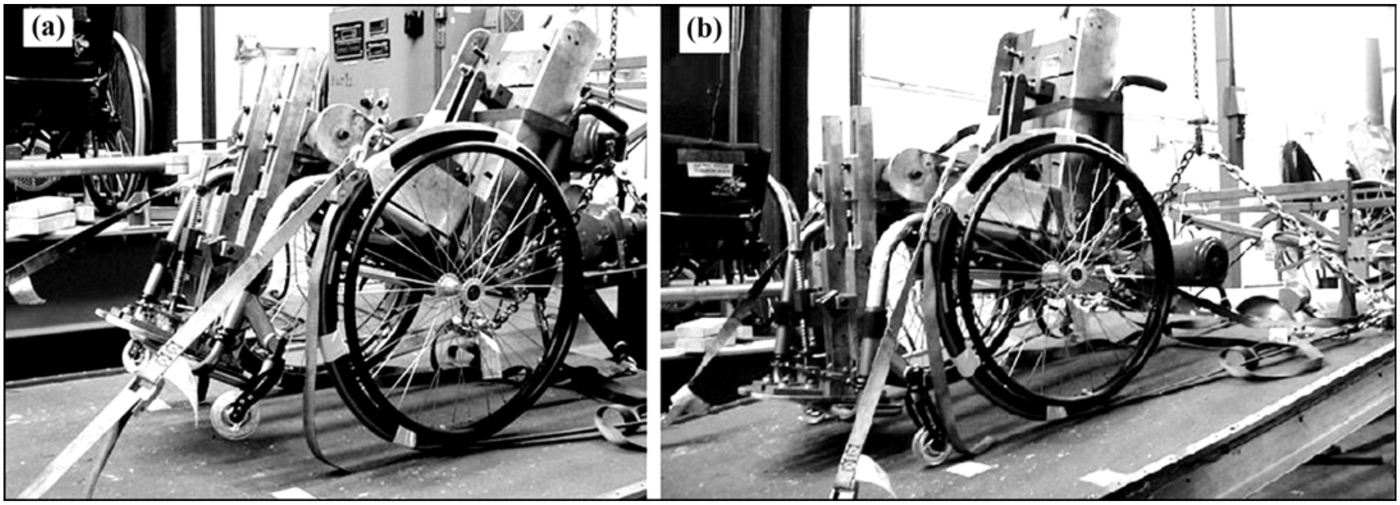

Figure 2.
Rearward stability test with wheelchair in least stable configuration and rear wheels locked. All rearward stability tests with wheelchairs in their least stable configurations had same modified testing method. **(a)** Wheelchairs were placed facing downhill and secured by straps to prevent them from tipping over completely, while angle was gradually increased until front casters lowered down to platform. **(b)** Angle was recorded when front casters touched platform.

wheelchair was loaded with a 100 kg dummy during the tests. In the DDT, the position of the drive wheels was set at the midaxle position according to the requirements in the standards. Because the titanium wheelchairs were unstable in this position, we set the rear axles in the most rearward position horizontally and the midposition vertically (which was how they arrived from the suppliers). Other wheelchair settings were set according to the requirements in the standard. The leg length of the dummy was adjusted to fit the wheelchair dimensions, and the feet were fixed on the footrests. The dummy's trunk and legs were secured to the wheelchair, although hip-joint motion was preserved through a spring-loaded damper system that allowed physiological-like motion during the testing. According to the standard, the dummy was positioned centrally on the seat. Generally, the weight of both legs is 32 percent of total body weight [14]. Individuals who are 6 months post spinal cord injury may lose 15 to 46 percent of their lower-limb muscle area [15]. We carefully kept the weight-loading on the front casters within 20 to 25 percent of the total weight of the dummy and the wheelchair to approximate the influence of the occupant's body weight and the weight of the wheelchair and prevent overloading on the casters by adjusting the location of the dummy either in an anterior or posterior direction. The 12 mm-high slats on the drum simulate sidewalk cracks, door thresholds, potholes, and other small obstacles on the rolling surface. Two clamps attached to the rear-wheel axle held the position and balance of the wheelchair on the double-drum machine but allowed vertical movement without appreciable sideward drift (**Figure 3**). The rear drum runs at a speed of 1 m/s, and the front drum turns 7 percent faster to vary the frequency with which the front and rear wheels encounter the slats. A wheelchair that completed 200,000 cycles on the test machine was considered to have passed the DDT.

Only the wheelchairs that passed the DDT continued on to the CDT. In the CDT, the wheelchair was repeatedly dropped freely from a 5 cm height onto a concrete floor to simulate going down small curbs. A wheelchair passes the wheelchair standard tests when it survives 200,000 cycles in the DDT and 6,666 cycles in the CDT without harmful damage [1]. The intensity of the fatigue tests mimics 3 to 5 years of daily use [16]. We repeated the fatigue tests until each wheelchair had permanent damage to determine the exact survival life. For the purpose of comparing fatigue life, we used the following formula to compute the number of equivalent cycles (ECs) [2,6–7]:

$$\text{Total ECs} = (\text{DDT cycles}) + 30 \times (\text{CDT cycles}). \quad \mathbf{(1)}$$

Figure 3.
Setting of double-drum test. Two clamps attached to rear-wheel axle held position and balance of wheelchair on double-drum machine but allowed vertical movement without appreciable sideward drift.

The EC counts the number of cycles before the occurrence of a class III failure in the fatigue test. A wheelchair that obtained an EC score of 400,000 cycles was denoted as passing the minimum requirements of the standard.

Failure severity was classified into three levels. Any failures, such as tightening screws or bolts or inflating the tires, that could be repaired by the user or any untrained personnel were counted as class I failures. Class II failures, such as replacing tires or spokes and doing complex adjustments, need to be repaired by a wheelchair or bicycle technician [16]. Permanent damage to the frame or any failure that would put the user in a hazardous situation was counted as a class III failure in this study. In a previous ultralight wheelchair comparison study, three bolt failures were considered class III failures [2]. Multiple minor failures were not counted as class III failures in this study to prevent premature discontinuation that would shelter the durability of the main frame and structure. All the failures were recorded to disclose the frequency and complexity of the repairs needed for each wheelchair.

Cost-Effectiveness

Knowing the cost-effectiveness of a wheelchair is meaningful. We compared the cost-effectiveness of our test wheelchairs using the value derived from normalizing the number of ECs by the retail price of the wheelchair (cycles/dollar). The higher the value, the more cost-effective the wheelchair was deemed to be [3].

Data Analysis

We performed primary analyses for static stability, braking effectiveness, EC, and cost-effectiveness using Kruskal-Wallis tests, followed by Mann Whitney *U* tests as univariate analyses with the level of significance set at $p < 0.05$. Nonparametric statistical methods were used because the data were not normally distributed and the sample size was small [17].

We used the Kaplan Meier survival analysis method to compare cumulative survival rate [6] of titanium, ultralight, lightweight, and depot wheelchairs. A class III failure was defined as the terminal event in each group of wheelchairs [6].

RESULTS

The general features of the wheelchairs are presented in **Table 1**. All the chairs were rigid frame with one-piece footrests.

Static Stability

The mean ± standard deviation tipping angles are shown in **Table 2**. Significant differences were found in two test sections: the forward stability test in the most stable configuration with wheels unlocked ($p = 0.03$) and the rearward stability test in the least stable configuration with wheels unlocked ($p = 0.047$). The Quickie Ti with the front wheels (casters) unlocked and in the most stable setting was the most stable model in the forward stability test. The Invacare Top End with the rear wheels unlocked and in the least stable setting was the most stable model in the rearward stability test.

In the ANSI/RESNA wheelchair standard tests manual, the instructions indicate to move the rear wheel position forward when conducting forward stability tests. When testing this group of titanium wheelchairs, we considered the midposition of the rear-wheel axle the least stable setting (**Figure 4(a)**), since the wheelchair would tip backward if we moved the axle further forward (**Figure 4(b)**).

The range in the last column of each section of **Table 2** is the difference between the least and most stable tipping angles, which indicates the adjustable variability of the center of gravity for the wheelchair. Significant differences were found among the four models in the forward direction

Table 1.
Overall dimensions and features of titanium rigid-frame wheelchairs.

Parameter	Invacare Top End	Invacare A4	Quickie Ti	TiLite ZRA
Manufacturer	Invacare[*]	Invacare[*]	Sunrise Medical[†]	TiLite[‡]
Rear Wheels[§]	Sunrims CR20	SW6000 Sunrims	SW6000 Sunrims	Sunrims CR20
Tires				
Type	Pneumatic Pr1mo V-Trak	Pneumatic Knobby Pr1mo V-Trak	Pneumatic Knobby Pr1mo V-Trak	Pneumatic Pr1mo V-Trak
Recommended Pressure (psi)	100	75	75	100
Caster Diameter (mm)	80	80	80	80
Mass (kg)	9.1	11.3	9.1	9.1
Overall Length (mm)	797	827	820	807
Overall Width (mm)	632	643	603	587
Seat Angle (°)	10.3	7.6–11.8	8.5–23.6	4.9–18.7
Backrest Angle (°)	14.0	2.1–14.6	5.2–22.2	2.0–21.3
Horizontal Location of Rear Wheel Axle (mm)[¶]	16.7–106.3	26.7–154.3	28.0–140.7	15.5–143.0

[*] Invacare; Elyria, Ohio.
[†] Sunrise Medical; Longmont, Colorado.
[‡] TiLite; Kennewick, Washington.
[§] All rear wheels 610 mm in size.
[¶] Horizontal distance between rear wheel axle and intersection of references of backrest and seat plane according to ANSI/RESNA standards. All horizontal rear wheel locations were forward from intersection of backrest and seat plane.
ANSI = American National Standards Institute, RESNA = Rehabilitation Engineering and Assistive Technology Society of North America.

Table 2.
Tipping angle mean ± standard deviation and range in static stability tests.

Model	Forward (°)			Rearward (°)					
	Front Wheel Unlocked			Rear Wheel Locked			Rear Wheel Unlocked		
	Least Stable	Most Stable	Range	Least Stable	Most Stable	Range	Least Stable	Most Stable	Range
Invacare Top End[*]	25.7 ± 0.6	26.9 ± 1.5	1.2 ± 0.1[†]	–1.3 ± 3.9	10.9 ± 0.2	12.2 ± 3.9[†]	1.0 ± 7.3[†]	20.3 ± 1.1	19.3 ± 8.4[†]
Invacare A4[*]	24.2 ± 1.8	32.0 ± 1.1	7.8 ± 1.6	–16.9 ± 8.2	10.6 ± 2.9	27.5 ± 5.4	–15.0 ± 2.9	20.9 ± 4.7	35.9 ± 6.0
Quickie Ti[‡]	20.9 ± 1.8	34.3 ± 0.3[†]	13.4 ± 1.6[†]	–11.9 ± 1.6	14.6 ± 2.2	26.5 ± 2.9	–21.7 ± 6.0	27.1 ± 2.2	48.8 ± 4.3[†]
TiLite ZRA[§]	22.0 ± 0.4	31.4 ± 1.7	9.5 ± 1.6	–11.0 ± 2.7	10.1 ± 1.3	21.1 ± 1.4	–17.5 ± 3.1	18.3 ± 3.1	35.8 ± 1.3

Note: Range is difference in tipping angle between most stable and least stable configurations.
[*] Invacare; Elyria, Ohio.
[†] Result is significantly different from other models.
[‡] Sunrise Medical; Longmont, Colorado.
[§] TiLite; Kennewick, Washington.

with the rear wheels unlocked ($p = 0.02$), the rearward direction with the rear wheels locked ($p = 0.03$), and the rearward direction with the rear wheels unlocked ($p = 0.03$). The Invacare Top End had the least range in the forward and rearward stability tests. The Quickie Ti wheelchair with the rear wheels unlocked had the largest range in the forward and rearward stability tests. Tipping angle differences between the least and most stable wheelchair settings can give users and clinicians a general idea how much the center of gravity can be adjusted for the specific type of wheelchair (**Table 2**, range columns).

Braking Effectiveness

The sliding angles in the braking effectiveness tests (forward and rearward) are shown in **Table 3**. No significant differences were found among the four models in the forward or rearward directions. **Table 3** shows the individual data to reveal the performance of each wheelchair.

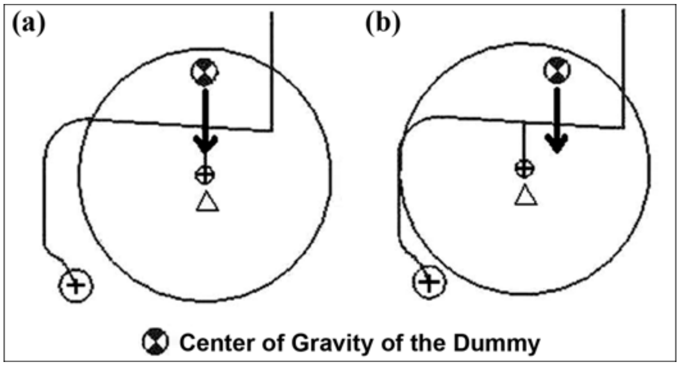

Figure 4.
Position of rear-wheel axle in forward stability tests. **(a)** Midposition of rear-wheel axle was considered least stable setting, since **(b)** wheelchair would tip backward if we moved axle further forward.

All of the wheelchairs passed the forward braking test. Every chair in this study tipped backward without sliding in the rearward braking effectiveness test, and two chairs of each model tipped prematurely before the platform inclined to 7°.

Impact and Static Strength Tests

All titanium wheelchairs passed the impact strength tests. Two types of failures were found in the static strength tests. Two Invacare Top End wheelchairs and one Invacare A4 wheelchair failed because of deformation of the armrest mounting plates after a 760 N downward force was applied on the armrests. This force caused the undamaged removable armrests to bow outward, which would impede the propulsion movement of the hands (**Figure 5(a)**). All the handgrips of the TiLite ZRA wheelchairs slid off the handles when a 750 N backward-pulling force was applied to the handgrips (**Figure 5(b)**).

Fatigue Strength Tests (Durability Testing), Equivalent Cycles, and Cost-Effectiveness

No significant differences were found in the number of ECs among the four models. The Invacare A4 had the highest number of mean ECs, and the TiLite ZRA had the lowest number of ECs. The ECs and cost-effectiveness (in terms of value) of each model are shown in **Table 4**. Only 4 titanium wheelchairs out of 12 met the 200,000-cycle requirement for the DDT. Two Invacare A4 and one Invacare Top End wheelchairs passed the standard (**Figure 6**) (i.e., successfully completed the DDT and CDT). The titanium ultralight rigid-frame wheelchairs had significantly less ECs than the aluminum ultralight folding wheelchairs ($p < 0.001$), but their ECs were not significantly different from those of the lightweight steel wheelchairs ($p = 0.57$).

The manufacturer's suggested retail price of the Invacare Top End was $3,218, Invacare A4 was $2,875, Quickie Ti was $2,995, and TiLite ZRA was $2,695. These prices were for the wheelchair configurations tested in this study. The Invacare A4 had the highest value and the TiLite ZRA had the lowest value (**Table 4**), but no significant differences were found among the four models. Compared with previously tested aluminum ultralight folding and steel lightweight wheelchairs, these titanium wheelchairs had significantly less value ($p <$ 0.001 and 0.006, respectively).

The numbers of class I and II failures that occurred before the final class III failure are shown in **Figure 7**. The Invacare A4-11 and TiLite ZRA-10 experienced the highest number of failures (four times) before permanent damage occurred. Three of the class II failures of the TiLite ZRA-10 were the spokes of the rear wheel, not frame failures. If the wheel failures were not counted, eight wheelchairs experienced only 1 or 0 class I or class

Table 3.
Sliding angle in braking effectiveness tests.

Parameter	Invacare Top End[*] Wheelchair No.			Invacare A4[*] Wheelchair No.			Quickie Ti[†] Wheelchair No.			TiLite ZRA[‡] Wheelchair No.		
	03	04	05	06	11	12	07	08	09	01	02	10
Sliding Angle: Forward (°)	19.5	17.1	21.2	35	14.4	17.2	25.1	10	12.8	12	14	8.3
Sliding Angle: Rearward (°)	12.4	5.4[§]	4.2[§]	15	6.1[§]	3.1[§]	3.4[§]	9.4	5.6[§]	10	6.5[§]	5.9[§]

[*] Invacare; Elyria, Ohio.
[†] Sunrise Medical; Longmont, Colorado.
[‡] TiLite; Kennewick, Washington.
[§] Wheelchair tipped backward before platform inclined to 7°.

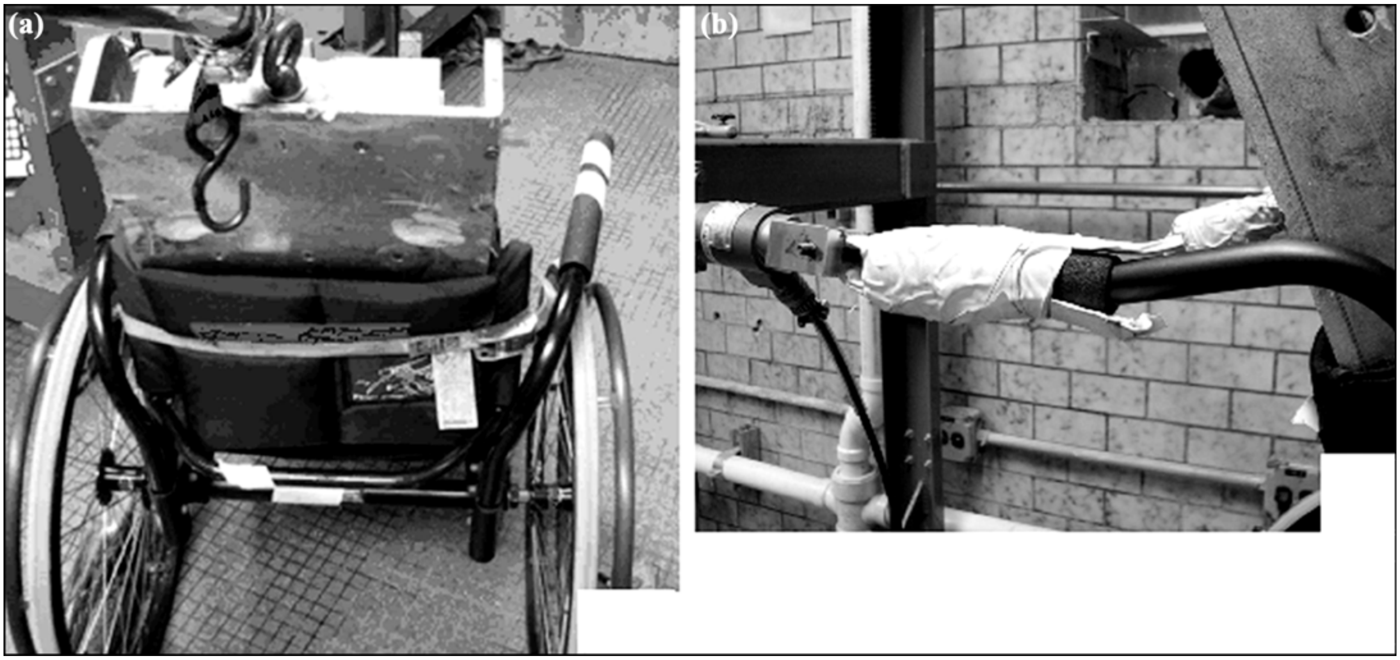

Figure 5.
Two failures in static strength tests. **(a)** Invacare Top End armrest position deviated because of deformation of armrest mounting piece after 760 N downward force was applied. Shifted location of armrest would impede propulsion movement of hands. **(b)** TiLite ZRA handgrip slid off handle after 750 N backward-pulling force was applied.

Table 4.
Equivalent cycles and value of titanium manual wheelchairs. All data presented as mean ± standard deviation.

Model	Equivalent Cycles	Value (cycles/$)
Invacare Top End*	218,945.7 ± 186,128.9	68.0 ± 57.8
Invacare A4*	390,097.7 ± 191,420.4	135.7 ± 66.6
Quickie Ti†	224,732.7 ± 151,797.9	75.0 ± 50.7
TiLite ZRA‡	152,249.3 ± 57,929.4	56.5 ± 21.5

*Invacare, Corp; Elyria, Ohio.
†Sunrise Medical; Longmont, Colorado.
‡TiLite; Kennewick, Washington.

II failures before catastrophic frame failures occurred. Each minor failure (class I and II) and the permanent failure (class III) are listed in **Table 5**. The failure mode was quite consistent within the model of titanium rigid-frame wheelchair.

DISCUSSION

Lighter weight and more compact dimensions can improve the maneuverability and transportability of a wheelchair [11]. This group of titanium rigid-frame wheelchairs tends to have smaller dimensions and lighter weight than wheelchairs with swing-away footrests of the same seat dimensions. Titanium wheelchairs are expected to increase mobility and efficiency in daily living. However, the general features do not endorse this group of titanium wheelchairs as the best choice for manual wheelchair users. Multiple factors affect satisfaction and usage of wheelchairs [10,18].

The results of this study reject our previous hypotheses that these titanium wheelchairs would be in compliance with ANSI/RESNA standards and more durable

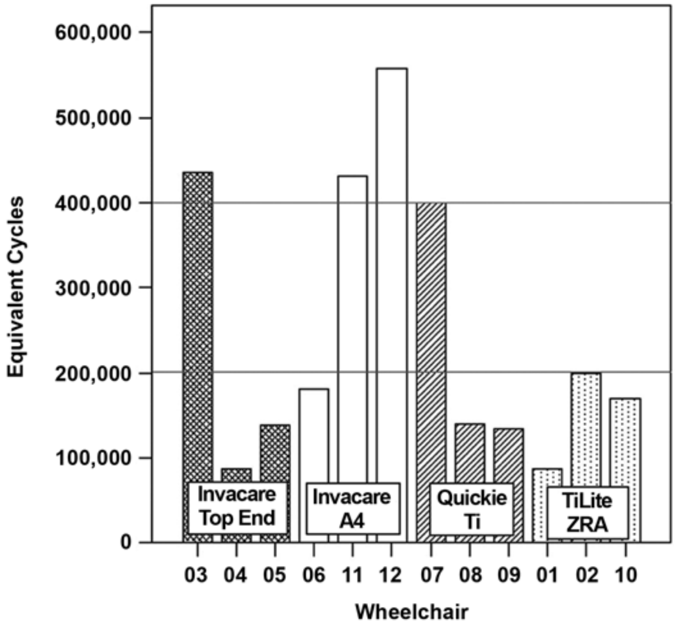

Figure 6.
Equivalent cycles of each wheelchair in fatigue tests. Horizontal line at 200,000 cycles indicates required testing cycles in double-drum test. Line at 400,000 cycles represents minimum request in American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America wheelchair standard.

than previously tested aluminum ultralight wheelchairs and lightweight wheelchairs. Discussions according to the sections in the standards tests follow.

Static Stability

This group of titanium wheelchairs with rigid frames had greater tipping angle differences between the least and most stable settings in each stability test than the aluminum ultralight wheelchairs in our previous study [2]. The folding-frame aluminum wheelchairs with X-bars and swing-away footrests had the center of gravity in a more forward position than the rigid-frame wheelchairs. The position of the dummy's lower limbs on the wheelchair may also make the test results different from the previous study. In this study, the dummy's legs were bent farther backward than they were in our previous tests of aluminum ultralight wheelchairs. This position shifted the center of gravity backward and thereby decreased the rearward stability. Although this setting with negative tipping angles is not practical in the real world, our results indicate that these wheelchairs have great variability in the center of gravity adjustment of the user/wheelchair system relative to the axle position. Our results suggest that the stability of this group of rigid-frame wheelchairs may be changed significantly by moving the axle position subtly. Suppliers and clinicians who use this group of wheelchairs should check and adjust the rear wheel axle with caution, especially when providing service to novice users.

Braking Effectiveness

The wheelchairs in this study stayed stationary in the forward direction on a slope that was steeper than the maximum incline degree prescribed by the ADA. However, most of the wheelchairs tipped on the >7° slope in the rearward braking effectiveness test. The frame design and the position of the dummy's lower-limbs did play an important role in affecting rearward stability as we discussed previously. The compact dimensions of the wheelchairs with rigid frames increase their maneuverability but decrease their rearward stability. Users have to adjust their trunk posture carefully to compensate for displacement

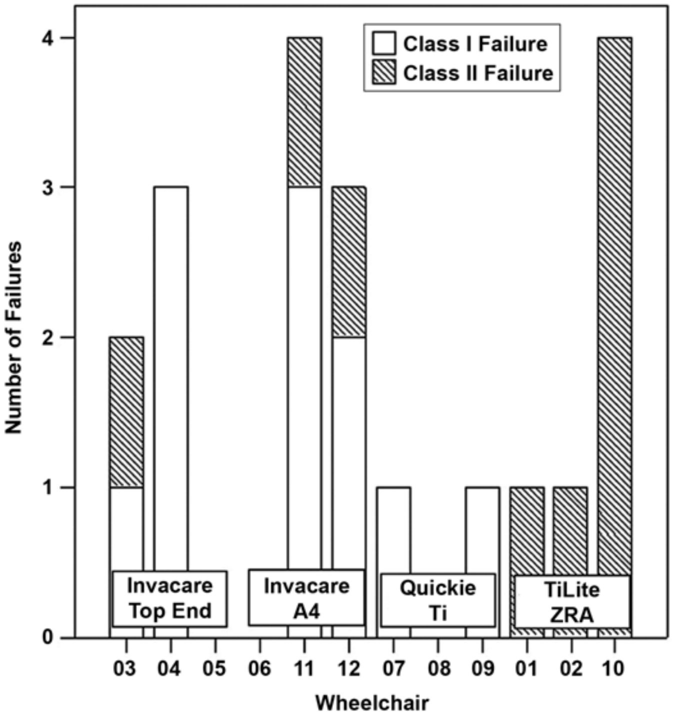

Figure 7.
Numbers of class I and II failures that occurred during fatigue tests before class III failure.

Table 5.
Failure mode in fatigue tests.

Wheelchair	Class I and II Failures	Class III Failures
Invacare Top End-03*	Right rear-wheel axle screw slid out; backrest upholstery was worn out.	Both backrest canes fractured.
Invacare Top End-04*	Right rear-wheel axle screw slid out 3×.	Both backrest canes fractured.
Invacare Top End-05*	—	Left backrest cane fractured.
Invacare A4-06*	—	Right caster stem fractured; frame fractured through screw hole at midway of seat on right side; both rear wheels could not be taken off from quick-release axle.
Invacare A4-11*	Footrest slid down; rear-wheel axle slid forward; footrest left suspension tube fractured; left rear-wheel axle slid out.	Right frame tube fractured at screw hole for mounting piece between backrest and seat.
Invacare A4-12*	Seat sling detached from frame; footrest slid down 2×.	Right frame tube fractured at screw hole for mounting piece between backrest and seat.
Quickie Ti-07†	Left caster screw loosened.	Left frame tube fractured at first screw hole of seat.
Quickie Ti-08†	—	Frame tube fractured at left first screw hole and was torn at right second screw hole of seat.
Quickie Ti-09†	Right caster screw loosened.	Left frame tube fractured at second screw hole of seat.
TiLite ZRA-01‡	Plastic plate of footrest chipped.	Right frame tube fractured at first screw hole of seat.
TiLite ZRA-02‡	Plastic plate of footrest chipped.	Right frame tube fractured at first screw hole of seat; right rear wheel could not be taken off from quick-release axle.
TiLite ZRA-10‡	Eight spokes of right rear wheel detached sequentially; plastic plate of footrest chipped.	Right frame tube fractured at first screw hole of seat.

*Invacare; Elyria, Ohio.
†Sunrise Medical; Longmont, Colorado.
‡TiLite; Kennewick, Washington.

of the center of gravity when pushing one of these four wheelchair models uphill. Novice users must be educated about this behavior and trained in wheelchair skills to manage on slopes.

Impact and Static Strength Tests

Although the three Invacare wheelchairs that failed in the armrest static strength test were still usable, the compromised material strength of the mounting plates could have caused a catastrophic failure (**Figure 5(a)**). The TiLite wheelchairs had a similar mounting mechanism for the armrest as the Invacare wheelchairs, but they had a stronger structure, having double plates to support the armrest bar. All of the TiLite wheelchairs failed in the handgrip static strength tests. The hazard will occur when an attendant is pulling the wheelchair backward with an occupant in it. The attendant would tend to fall backward when the handgrips slide off the handles. Moreover, the situation may endanger the user, who could roll away uncontrolled.

Fatigue Strength Tests (Durability Testing)

This group of titanium wheelchairs survived fewer ECs (their average EC was 246,506 ± 154,086) than was previously reported for aluminum ultralight wheelchairs, but their life expectancy was similar to that of steel lightweight wheelchairs [2–3]. Besides, the titanium rigid-frame wheelchairs exhibited less value than the aluminum ultralight and the steel lightweight wheelchairs (**Figure 8**). **Figure 8** shows the value of each wheelchair model for titanium ultralight rigid-frame, aluminum ultralight folding-frame, and steel lightweight wheelchairs, respectively, and the average value of each group according to the results from this and previous studies. Although the results were different among manufacturers, the wheelchairs in each group had similar performances. The survival curves

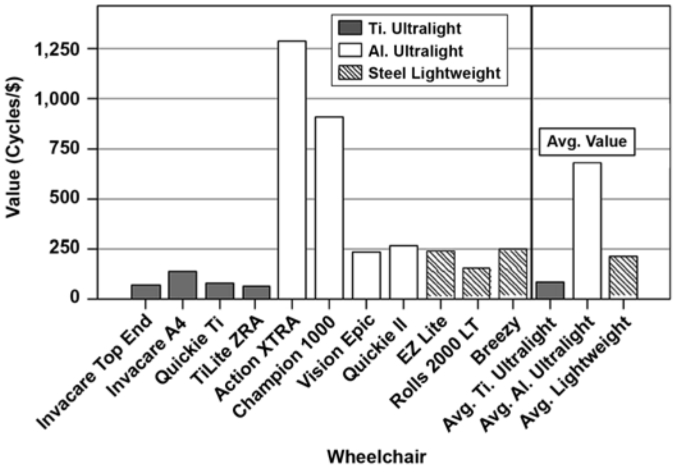

Figure 8.
Value (cycles/$) of titanium (Ti.) ultralight, aluminum (Al.) ultralight, and steel lightweight wheelchairs. Final three columns are average (Avg.) value for three types of manual wheelchairs.

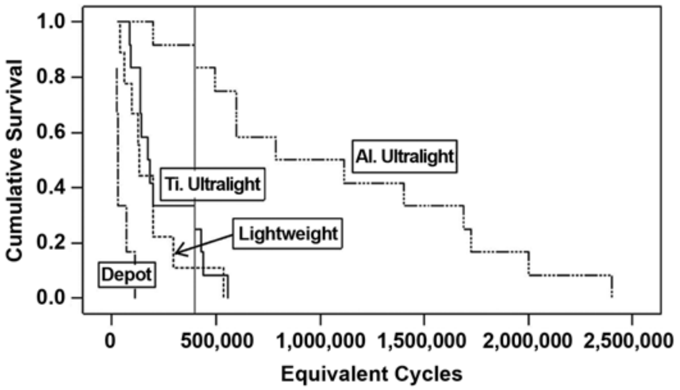

Figure 9.
Survival curves for titanium (Ti.) ultralight, aluminum (Al.) ultralight, lightweight, and depot wheelchairs from this and previous comparison studies [1–3]. Gray vertical line indicates 400,000 cycle equivalent, which indicates passing durability standard. 1. Cooper RA, Boninger ML, Rentschler A. Evaluation of selected ultralight manual wheelchairs using ANSI/RESNA standards. Arch Phys Med Rehabil. 1999;80(4): 462–67. [PMID: 10206612]. 2. Cooper RA, Gonzalez J, Lawrence B, Renschler A, Boninger ML, VanSickle DP. Performance of selected lightweight wheelchairs on ANSI/RESNA tests. American National Standards Institute-Rehabilitation Engineering and Assistive Technology Society of North America. Arch Phys Med Rehabil. 1997;78(10): 1138–44. [PMID: 9339166]. 3. Cooper RA, Robertson RN, Lawrence B, Heil T, Albright SJ, VanSickle DP, Gonzalez J. Life-cycle analysis of depot versus rehabilitation manual wheelchairs. J Rehabil Res Dev. 1996;33(1):45–55. [PMID: 8868417]

(**Figure 9**) show each step going down, indicating class III failures of the wheelchairs from each group. With 400,000 ECs the minimum requirement of ANSI/RESNA standards, 80 percent of the aluminum ultralight wheelchairs survived but less than 40 percent of the titanium rigid-frame wheelchairs survived to comply with current standards. The aluminum ultralight wheelchairs lasted about four times longer and had a value of about eight times higher than the wheelchairs in this study. Although a smaller caster size increases the impact load on the frame compared with the larger 203 mm casters on previously tested aluminum wheelchairs, testing these titanium rigid-frame wheelchairs with 80 mm casters is reasonable based on the following. First, 80 mm casters are the standard components of the titanium wheelchairs tested in this study. According to the clinical experience of the clinicians in the Center for Assistive Technology at the University of Pittsburgh Medical Center, most users of this group of wheelchairs were prescribed these casters. Second, 203 mm casters are not available on these wheelchairs because the footrest and likely the users' feet would interfere with the free movement of these larger sized casters. If the test results of a wheelchair with its standard components are not revealed, estimating the quality and properties of the wheelchair after adjustment or with modification may be difficult.

The test results of aluminum folding wheelchairs and titanium rigid-frame wheelchairs should be compared directly, even though they have casters of different sizes. The clinical guideline recommends that manual wheelchair users use lighter wheelchairs but gives no specific recommendation on caster size [12]. Thus, manual wheelchair users at any level of injury or wheelchair skill may choose one of the ultralight titanium rigid-frame wheelchairs with 80 mm casters tested in this study or an ultralight aluminum folding-frame wheelchair with 203 mm casters. Therefore, all types of wheelchairs should be tested with their various components to disclose their influence on performance of the wheelchairs and all test results of different types of wheelchairs should be directly compared to provide complete information for the consumer.

The wheelchairs in this study had an estimated average usable life of 1.85 to 3.08 years based on the approximation that the intensity of the ANSI/RESNA fatigue tests represents regular use for 3 to 5 years [16]. The Invacare and TiLite wheelchairs include a lifetime warranty, and the Quickie wheelchair includes a 5-year warranty on the titanium frame. A large discrepancy seems to exist between the warranty provided by the manufacturers and the test results in this study. To provide more reliable information to the consumer, manufacturers should disclose their testing methods and setup to determine the durability of their products.

Failure Modes

Invacare Top End

All of the Invacare Top End wheelchairs experienced fractures of the backrest canes. On the Invacare Top End-04, we found white, light blue, straw, and gray colors in the weld vicinity on the inner surface of the fracture site (**Figure 10**). The colors on the inner surface were within the heat-affected zone, which indicates that the titanium had high levels of oxygen contamination during the welding process [19]. The fracture surface in the picture is quite shiny and without plastic deformation. This implies that embrittlement may have contributed to the fracture of the backrest cane.

The other two Invacare Top End wheelchairs both fractured in the same area on the backrest canes around the welding site connecting the backrest crossbar (**Figure 11 (a)(i)**) and the top corner of the gusset (**Figure 11(a)(ii)**) without the evidence of oxygen contamination. Because of the anterior and posterior movement of the dummy hitting the backrest during the DDT, the superior area of the gusset was in the bending stress concentration point of the cantilever structure [20]. Additionally, a hole is present at the intersection of the backrest and the backrest crossbar (**Figure 11(b)–(c)**) for inserting the gas flow to prevent oxygen contamination from welding. One of the backrest canes fractured at this hole (**Figure 11(c)**) because it further weakened the structure strength. The other three fractured backrest canes were broken at the superior edge of the weld area with the crossbar. Heat treatment from welding likely decreased the strength of the titanium canes. The Invacare Top End had the same backrest-cane wall thickness as the Quickie Ti and TiLite ZRA (1.27 mm) and was slightly thinner than the Invacare A4 (2.29 mm) (**Table 6**). The Invacare Top End was the only model where all chairs fractured at the backrest canes. The four factors—the cantilever structure of the backrest, one weld area for the backrest crossbar on the backrest, a second weld area for the gusset on the backrest, and the hole for inserting the gas shield—all contributed to weaken the structure. Only the depot wheelchairs in our previous comparison study had similar failure rates as the Invacare Top End [4].

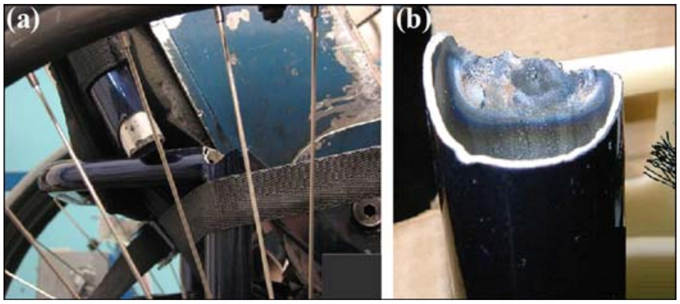

Figure 10.
Backrest cane fracture of Invacare Top End wheelchair in double-drum test (DDT). **(a)** Condition of failure in DDT with dummy on wheelchair. **(b)** Evidence of oxygen contamination that made inner surface of tube white, light blue, straw, and gray.

Invacare A4

The Invacare A4-06 fractured at the right caster stem and the middle of the right tube in the seat plane in the first round of the DDT (**Figure 12**). Although the caster stem was made of steel, the beach marks on the fracture surface indicate the occurrence of metal fatigue (**Figure 12 (b)–(c)**) [21–22]. Because only one fractured caster stem occurred in this study, it may be considered a defective component due to a small crack developed during manufacturing. However, this finding suggests that caster-stem fracture is possible and may damage the frame and endanger the user.

There were five holes around the fracture at the middle of the right seat frame of the Invacare A4-06 (**Figure 13** and **Figure 14(i)**). The other two Invacare A4 wheelchairs that failed in the second round of the DDT had fractures around the screw holes of the mounting plate between the backrest and seat frame and the screw holes for the seat sling (**Figure 15** and **Figure 14(ii)**). All these holes on the frame were for the seat sling, the mounting pieces of the backrest, and the mounting bracket of the T-shaped armrest. It is very intuitive in manufacturing to drill holes for mounting components on a frame; however, the fracture lines passing through the holes implied that the structural strength was decreased by the holes. The drawing with the translucent pattern in **Figure 14** shows the proximity of the holes on the frame more clearly.

The footrests of the two Invacare A4 wheelchairs repeatedly slid down during the DDT. Although both the Invacare A4 and Top End wheelchairs had footrest tubes

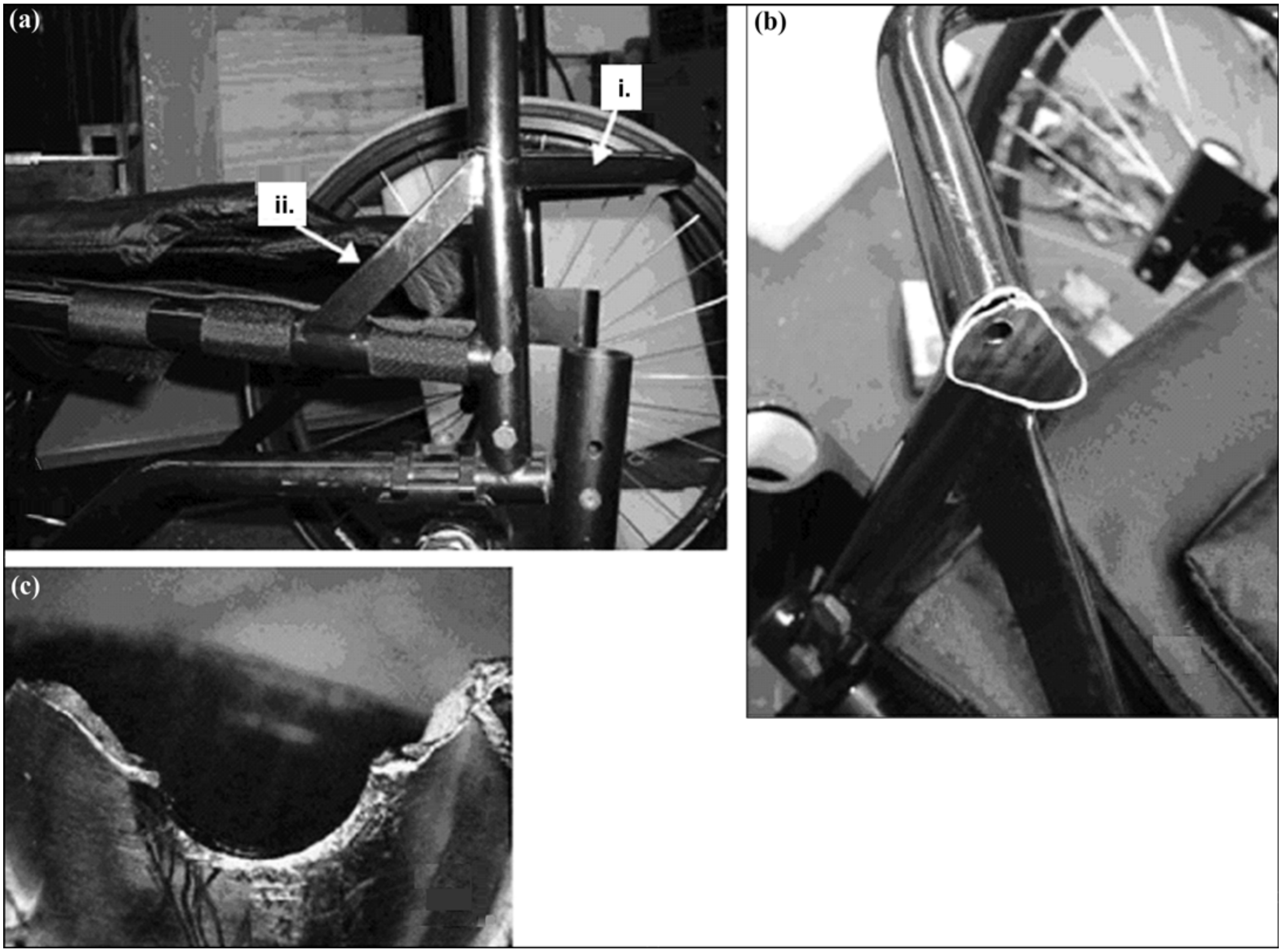

Figure 11.
Structure nearby fracture site of Invacare Top End wheelchairs. (**a**) Geometry relationship of backrest crossbar (i) and reinforce gusset (ii) with backrest cane. **(b)** Position of hole for inserting gas shield. **(c)** One backrest cane fractured right at gas insert hole.

clamped by only a set screw (**Figure 16(c)**), the A4 had a larger discrepancy in the diameter between the tube of the footrest and the outer piece of the main frame (**Table 6**). The strength of a set screw was not enough to compensate for the discrepancy in tube diameters and the vertical vibration from the dummy's legs during the DDT, so the footrest slid down. In real-world settings, a footrest keeps sliding down, bothering the user, because of the vertical vibration resulting from riding on uneven terrain or the occurrence of clonuses. Although this mounting mechanism of the footrest would not affect the integrity of the main frame, the unanticipated repositioning of the footrest can be inconvenient and potentially cause injury.

Quickie Ti and TiLite ZRA

The Quickie Ti and TiLite ZRA wheelchairs had the same type of failures at the first or second screw holes near the cantilever turn of the frame. These screw holes are used to mount the sling to the frame (**Figure 17**). Both models are cantilever frames (**Figure 18(a)**). The cantilever frame does not have the same lower longitudinal tubes as the box frame. The impact force (**Figure 18(a)(i)**) produced a bending torque (**Figure 18(a)(ii)**) that bent the front vertical part of the frame rearward. The bending torque compressed the lower part of the tube (**Figure 18 (a)(iii)**) and extended the upper part of the tube (**Figure 18 (a)(iv)**). The first and second screw holes were just rearward

Table 6.
Dimension of frame tubes and backrest canes.

Model	Frame Tube (mm)			Backrest Cane (mm)	
	Diameter	Thickness	Outer Diameter of Footrest Tube	Diameter	Thickness
Invacare Top End[*]	25.7	1.3	22.4	25.7	1.3
Invacare A4[*]	25.7	1.3[†]	19.1	25.7	2.3
Quickie Ti[‡]	25.7	1.3	19.1[§]	25.7	1.3
TiLite ZRA[¶]	31.8	1.5	19.1	25.7	1.3

[*] Invacare; Elyria, Ohio.
[†] Thickness of tube at seat plane of Invacare A4 is 1.02 mm.
[‡] Sunrise Medical; Longmont, Colorado.
[§] Inner diameter of clamp for footrest of Quickie Ti is 19.05 mm.
[¶] TiLite; Kennewick, Washington.

of the frame bend and acted as stress concentration points. Therefore, the fracture inevitably occurred at this location. In the box frame design (**Figure 18(b)**), the lower longitudinal tube helped to distribute the force transmitted to the casters (**Figure 18(b)(iii)**). This decreased the bending torque on the frame (**Figure 18 (b)(ii)**). The Invacare A4 had screw holes near the corner of the front frame as well, but the lower stresses helped protect the chair from failure at these stress concentration locations. Alternative ways are available to fix the seat sling onto the frame other than using screws. For example, the Invacare Top End Terminator everyday rigid wheelchair uses Velcro straps to attach the seat sling [23], which may have ameliorated the premature failures.

Wheelchair Material and Design

Titanium alloys have higher resistance to brittle fracture than aluminum alloys when a crack is present [22]. Although titanium has desirable mechanical properties, titanium is 1.6 times as heavy as aluminum. Balance between total weight of the product and structural strength needs to be considered carefully. The rigid-frame design and standard use of 80 mm casters are also critical issues that affect the stability and durability of this group of

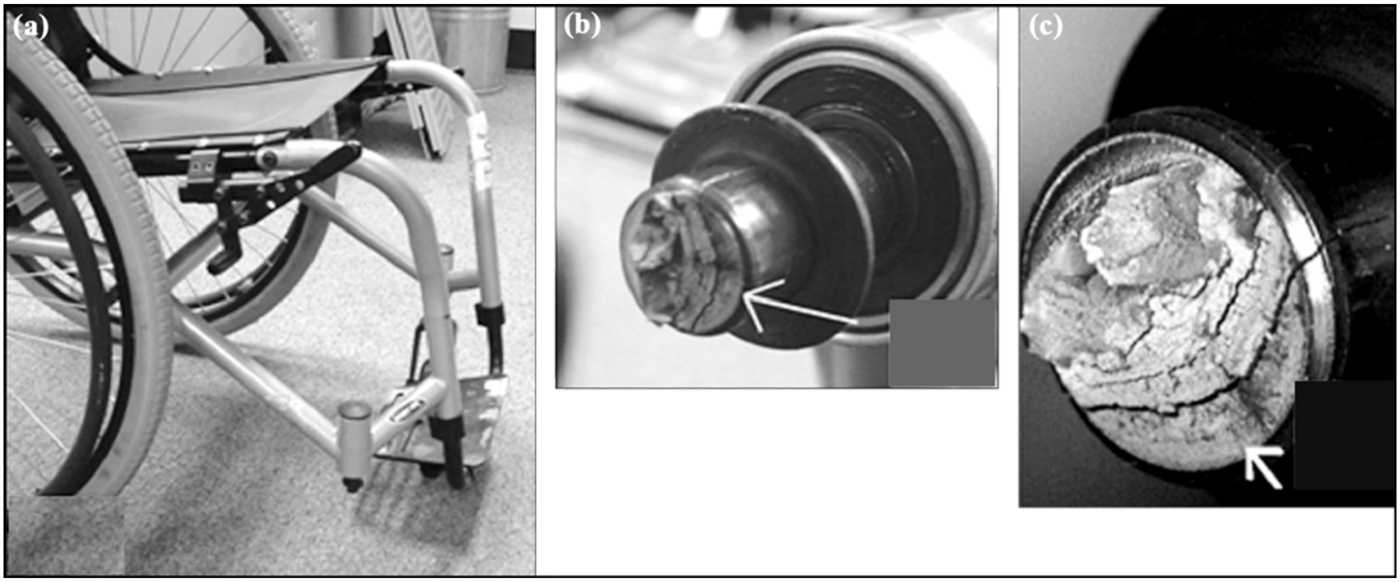

Figure 12.
Caster stem fracture of Invacare A4 wheelchair. **(a)** Location of caster stem fracture. **(b)–(c)** Fracture surface; arrows indicate start of crack that eventually developed into fatigue fracture.

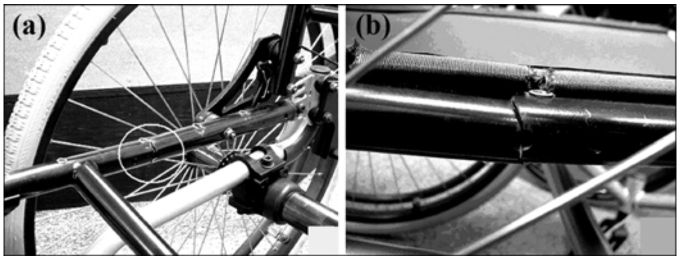

Figure 13.
Fracture at middle of tube in seat plane of Invacare A4. **(a)** Medial and **(b)** lateral view. Fracture lines in **(a)–(b)** were connected with each other.

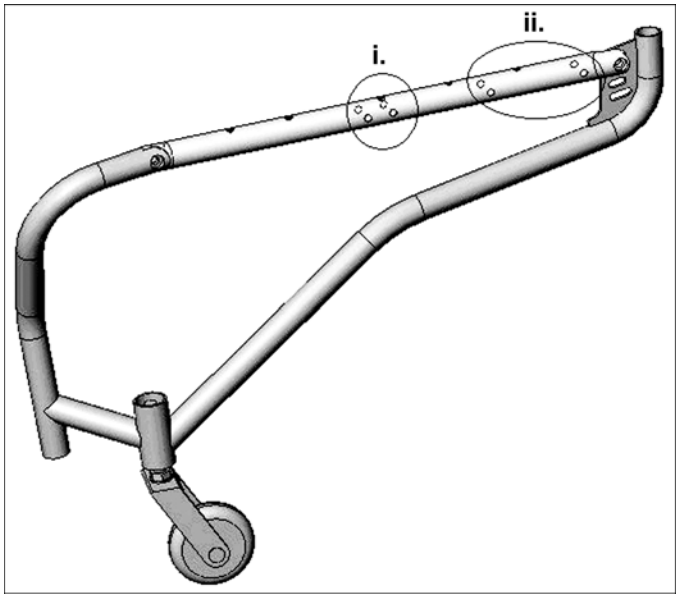

Figure 14.
Left frame of Invacare A4 showing locations of screw holes on tube in seat plane. (i) indicates fracture site at middle of seat plane of Invacare A4 wheelchair with caster stem fracture and (ii) indicates fracture site of other two Invacare A4 wheelchairs that went into second round of double-drum test.

wheelchairs. On the basis of our results, manufacturers and designers need to evaluate the rigid-frame titanium wheelchair designs in greater detail in order to understand the impact of material choices and mechanical design on the strength, durability, and function of the wheelchair. If the future direction will be to classify the wheelchairs with similar rigid-frame designs as those in this article into a specific group, the wheelchair standard tests may be considered to have modified testing methods and normative values for these wheelchair models.

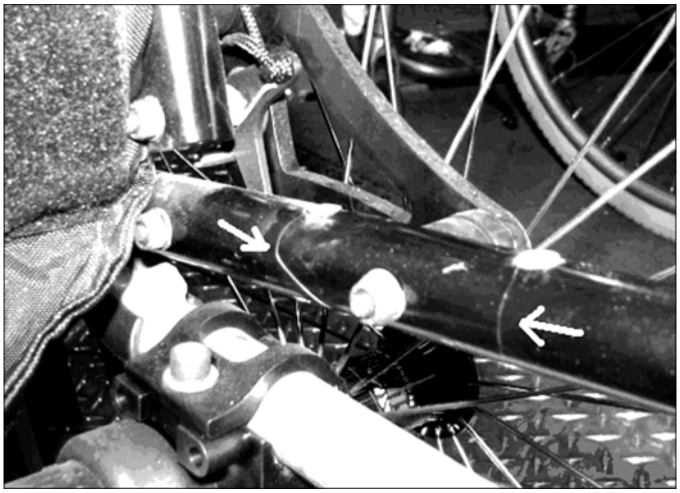

Figure 15.
Fracture lines (arrows) around screw holes for mounting plate between seat plane and backrest of Invacare A4 wheelchair.

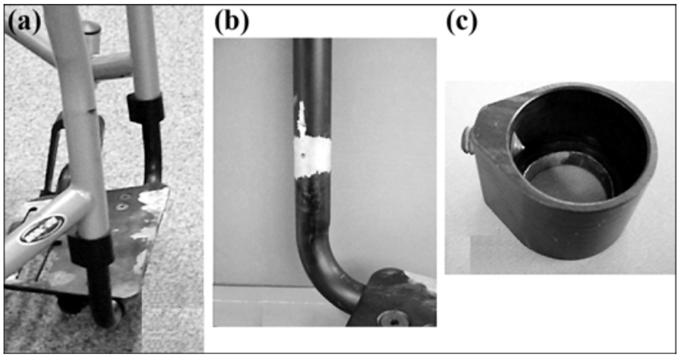

Figure 16.
Footrest of Invacare A4 wheelchair. **(a)** General structure of footrest. **(b)** Scratch by set screw on vertical footrest bar. **(c)** Structure of clamp and set screw.

Limitations

First, the sample size is a limitation of this study. We would have to test 12 to 60 wheelchairs of each model to have statistical power of 0.8, according to the test results in this study. It is not realistic to spend the time and money to test the required number of wheelchairs. Second, a test dummy cannot precisely simulate a real wheelchair user. A real wheelchair user could adjust his or her posture dynamically and avoid a situation that may endanger him- or herself or the wheelchair. For example, repeated impact from the dummy's trunk during the fatigue tests may not occur in real-world situations with this group of wheelchairs, but some users hang their backpacks on the

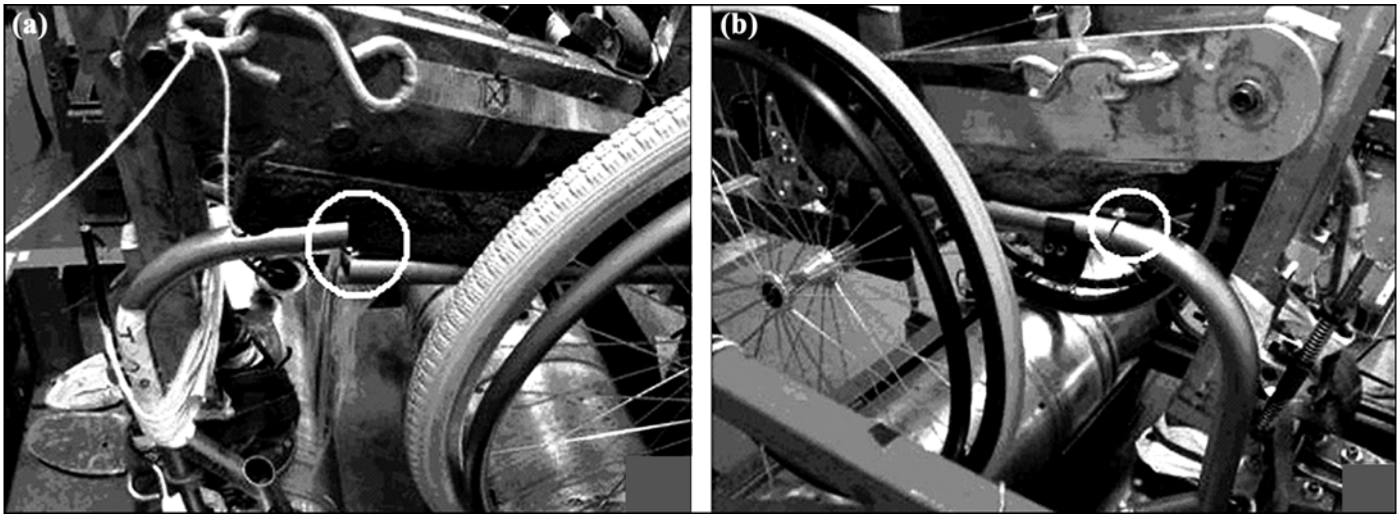

Figure 17.
Fracture in frame tube of wheelchair having cantilever structure along seat plane to footrest. **(a)** Fracture of Quickie Ti chair at second screw hole on left front frame. **(b)** Fracture of TiLite ZRA chair at first screw hole on right front frame.

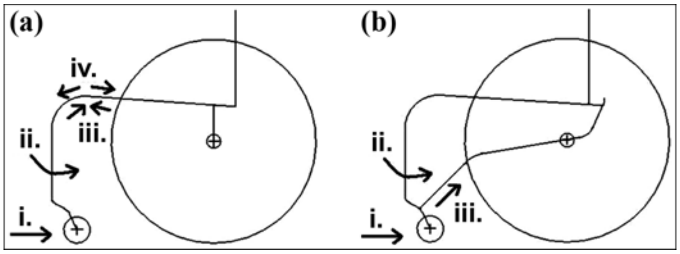

Figure 18.
Structure comparison between **(a)** cantilever frame and **(b)** box frame. For both types of frames, force (i) created torque (ii) that tended to bend front vertical part of frame. **(a)** In cantilever frame, force transmitting to frame tube compressed lower part of tube (iii) and stretched upper part of tube (iv)). First and second screw holes on upper part of tube are stress concentration and contributed to premature failure. **(b)** Box frame has lower longitudinal tubes which help to distribute stress (iii) from force (i), thus decreasing bending torque at vertical front part of frame.

backrests, which also causes bending stress on the backrests. ANSI/RESNA standard tests were originally designed to test K0001 wheelchairs 10 years ago, thus the requirements should not be as harsh for today's technology and manufacturing quality. Moreover, the test dummy weighs less than the maximum weight capacity of the wheelchairs in this study. Although the test dummy does not mimic a real wheelchair user completely, the general physical properties of the dummy actually produce less stress than the maximum weight capacity claimed by the manufacturers. Third, we could only draw general results from standard tests because the information was not thorough enough to discriminate the specific causes or mechanisms attributed to the vital failures in the fatigue tests. Therefore, future studies are needed to address these issues.

CONCLUSIONS

This group of rigid-frame titanium wheelchairs is widely prescribed. Their highly adjustable rear-wheel axles, ultralight weight, and compact dimensions help decrease physical stress on the user when propelling a wheelchair and increase ease of use. This study revealed important design concerns that need to be addressed. Our results should remind manufactures and designers that each weld point, screw hole, and change in structure and frame design has its impact on the strength and durability of the wheelchair. Our results indicate that manufacturers may need to perform more careful analyses before commercializing new products.

ACKNOWLEDGMENTS

This material was based on work supported by the Department of Veterans Affairs Rehabilitation Research and Development Service (grant B3142C) and the National Science Foundation—Integrative Graduate Education and Research Traineeship program (grant DGE 0333420).

The authors have declared that no competing interests exist.

REFERENCES

1. RESNA, American National Standards Institute. American national standard for wheelchairs. Arlington (VA): American National Standards Institute; 1998.
2. Cooper RA, Boninger ML, Rentschler A. Evaluation of selected ultralight manual wheelchairs using ANSI/RESNA standards. Arch Phys Med Rehabil. 1999;80(4): 462–67. [PMID: 10206612]
3. Cooper RA, Gonzalez J, Lawrence B, Renschler A, Boninger ML, VanSickle DP. Performance of selected lightweight wheelchairs on ANSI/RESNA tests. American National Standards Institute-Rehabilitation Engineering and Assistive Technology Society of North America. Arch Phys Med Rehabil. 1997;78(10):1138–44. [PMID: 9339166]
4. Cooper RA, Robertson RN, Lawrence B, Heil T, Albright SJ, VanSickle DP, Gonzalez J. Life-cycle analysis of depot versus rehabilitation manual wheelchairs. J Rehabil Res Dev. 1996;33(1):45–55. [PMID: 8868417]
5. Fass MV, Cooper RA, Fitzgerald SG, Schmeler M, Boninger ML, Algood SD, Ammer WA, Rentschler AJ, Duncan J. Durability, value, and reliability of selected electric powered wheelchairs. Arch Phys Med Rehabil. 2004; 85(5): 805–14. [PMID: 15129406]
6. Fitzgerald SG, Cooper RA, Boninger ML, Rentschler AJ. Comparison of fatigue life for 3 types of manual wheelchairs. Arch Phys Med Rehabil. 2001;82(10):1484–88. [PMID: 11588758]
7. Pearlman JL, Cooper RA, Karnawat J, Cooper R, Boninger ML. Evaluation of the safety and durability of low-cost nonprogrammable electric powered wheelchairs. Arch Phys Med Rehabil. 2005;86(12):2361–70. [PMID: 16344036]
8. Smith C, McCreadie M, Unsworth J. Prescribing wheelchairs: The opinions of wheelchair users and their carers. Clin Rehabil. 1995;9(1):74–80.
9. Trail M, Nelson N, Van JN, Appel SH, Lai EC. Wheelchair use by patients with amyotrophic lateral sclerosis: A survey of user characteristics and selection preferences. Arch Phys Med Rehabil. 2001;82(1):98–102. [PMID: 11239293]
10. Kittel A, Di MA, Stewart H. Factors influencing the decision to abandon manual wheelchairs for three individuals with a spinal cord injury. Disabil Rehabil. 2002;24(1–3): 106–14. [PMID: 11827144]
11. Rogers H, Berman S, Fails D, Jaser J. A comparison of functional mobility in standard vs. ultralight wheelchairs as measured by performance on a community obstacle course. Disabil Rehabil. 2003;25(19):1083–88. [PMID: 12944147]
12. Paralyzed Veterans of America Consortium for Spinal Cord Medicine. Preservation of upper limb function following spinal cord injury: A clinical practice guideline for health-care professionals. J Spinal Cord Med. 2005;28(5):434–70. [PMID: 16869091]
13. International Organization for Standardization (ISO). Wheelchairs—Part 3: Determination of effectiveness of brakes. ISO 7176-3:2003. Geneva (Switzerland): ISO; 2003.
14. Winter DA. Biomechanics and motor control of human movement. 3rd ed. Hoboken (NJ): John Wiley & Sons, Inc; 2005.
15. Giangregorio L, McCartney N. Bone loss and muscle atrophy in spinal cord injury: Epidemiology, fracture prediction, and rehabilitation strategies. J Spinal Cord Med. 2006;29(5): 489–500. [PMID: 17274487]
16. Cooper RA. Wheelchair standards and testing. Wheelchair selection and configuration. New York (NY): Demos; 1998. p. 165–95.
17. Munro BH. Selected nonparametric techniques. Statistic methods for health care research. Lippincott Williams & Wilkins; 2005. p. 109–36.
18. Di Marco A, Russell M, Masters M. Standards for wheelchair prescription. Aust Occup Ther J. 2003;50(1):30–39.
19. TWI Ltd [homepage on the Internet]. Cambridge (England): The Welding Institute; c2008 [updated 2008; cited 2007]. Weldability of materials: Titanium and titanium alloys; [about 4 screens]. Available from: http://www.twi.co.uk/j32k/protected/band_3/jk24.html/.
20. eFunda [homepage on the Internet]. Sunnyvale (CA): eFunda, Inc; c2008 [updated 2008; cited 2007 Jun 25]. Cantilever loading options; [about 1 screen]. Available from: http://www.efunda.com/formulae/solid_mechanics/beams/casestudy_bc_cantilever.cfm/.
21. Stephens RI, Faterini A, Stephens RR, Fuchs HO. Macro/micro aspects of fatigue of metals. Metal fatigue in engineering. Wiley-IEEE; 2001. p. 33–41.
22. Callister J. Materials science and engineering: An introduction. 3rd ed. New York (NY): Wiley; 1994.
23. Invacare. Owner's operator and maintenance manual. TOP END everyday and sport series wheelchairs. Elyria (OH): Invacare; 2007.

Submitted for publication December 7, 2007. Accepted in revised form June 23, 2008.