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Wheelchair tiedown and occupant restraint loading associated with adult manual transit wheelchair in rear impact

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Abstract—Proper securement of wheelchairs in motor vehicles is vital to providing wheelchair users an adequate level of safety in a crash. Thus far, wheelchair tiedown and occupant restraint systems (WTORS) loading has mostly been examined under frontal impact conditions. Because of the inherent crash dynamic differences, rear-impact loading of WTORS is expected to differ greatly. In this study, three identical, reinforced, manual, folding, X-braced ANSI/RESNA WC19 wheelchairs were subjected to an International Organization for Standardization-proposed rear-impact crash pulse. WTORS loads (front tiedowns, rear tiedowns, lap belt, and shoulder belt) were measured and compared with frontal impact WTORS loading. Rear impact produced substantially higher loads (up to 7,851 N) in the front tiedowns than frontal impact. The rear tiedowns experienced relatively negligible loading (up to 257 N) in rear impact, while rear-impact dynamics caused the lap belt (maximum load of 1,865 N) to be loaded substantially more than the shoulder belt (maximum load of 68 N). Considering differences in frontal and rear impact WTORS loading is important to proper WTORS design and, thus, protection of wheelchair-seated occupants subjected to rear-impact events.

Key words: ANSI/RESNA WC19, crash dynamics, loading, occupant restraints, rear impact, tiedowns, wheelchair safety, wheelchair securement, wheelchair transportation, WTORS.

INTRODUCTION

For persons with disabilities, access to transportation is necessary for integration into society. The Americans with Disabilities Act has been instrumental in assuring transportation access to individuals with disabilities for purposes of employment, education, and recreation [1]. Out of the 3.3 million wheelchair users in the United States [2], a substantial number may not be able to transfer from their wheelchair to a motor vehicle seat during transportation. It is necessary to afford these wheelchair users the same level of safety as occupants seated in motor vehicle seats.

The primary purpose of any wheelchair is to provide mobility for people with disabilities. However, many wheelchairs are not designed to serve as seats in a motor vehicle. This result is substantiated by the catastrophic failures shown in preliminary rear-impact sled tests conducted by the University of Michigan Transportation

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Abbreviations: ANSI/RESNA = American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America, ATD = anthropomorphic testing device, ISO = International Organization for Standardization, LB = lap belt, ORS = occupant restraint system, SAE = Society of Automotive Engineers, SB = shoulder belt, TC = Technical Committee, UMTRI = University of Michigan Transportation Research Institute, WTORS = wheelchair tiedown and occupant restraint systems.

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Research Institute (UMTRI) [3]. Some commercial wheelchairs are designed to be crashworthy in a frontal impact through compliance with the design and performance requirements of American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America (ANSI/RESNA) standard WC19: "Wheelchairs used as seats in motor vehicles" [4]. However, the dynamics of a rear-impact collision and thus the wheelchair, securement system, and occupant restraint loading are likely to differ greatly from those in frontal impact. It is important from a safety and product design perspective to investigate the loading conditions associated with rear-impact events, as they will directly affect wheelchair tiedown and occupant restraint systems (WTORS) integrity, wheelchair securement point integrity, and ultimately wheelchair occupant response to impact. If WTORS and wheelchair securement points are not properly designed, the wheelchair and/or wheelchair occupant may be ejected into the vehicle interior during impact [3].

For tiedown and wheelchair manufacturers to design securement systems and transit wheelchairs that are safe in a rear-impact event, they must understand the loading associated with rear impact. Rear-impact collisions are responsible for nearly 30 percent of all motor vehicle crash-related injuries [5] and 5.4 percent of fatalities [6]. These data are based on occupants using standard motor vehicle seats that are rigidly secured to the vehicle. Because wheelchairs may be structurally less stable than motor vehicle seats and after-market securement systems must be used, higher injury and death rates may occur in wheelchair-seated occupants for a given rear-impact event. Therefore, it was the goal of this study to quantify WTORS loading in rear impact to assist WTORS and wheelchair manufacturers in designing products with improved crashworthiness.

METHODS

Three identical, commercial, reinforced, manual, folding, X-braced wheelchairs (25.1 kg) that comply with ANSI/RESNA WC19 were subjected to three rear-impact sled tests using a rebound-type impact sled at UMTRI. We chose a manual wheelchair because the vast majority (83%) of wheeled mobility users use manual wheelchairs [7]. The ANSI/RESNA WC19 frontal impact compliant wheelchairs required reinforcement because previous rear-impact testing showed critical wheelchair failures (seatback failure, front securement point failure, and wheelchair frame failure) [3] that would substantially affect loading patterns. Three key wheelchair components were reinforced: (1) front securement point hardware, (2) seatback canes, and (3) horizontal wheelchair frame members (**Figure 1**). The front securement point hardware was upgraded using Society of Automotive Engineers (SAE) grade 8 bolts, while the seatback was reinforced with a 610 mm-long, 9.5 mm-diameter solid steel rod into each seatback cane. To address possible wheelchair frame failure, we inserted 11.6 mm-diameter steel rods into the horizontal members of the wheelchair tubular frame. The diameters of the steel rod inserts for the seatback canes and wheelchair frame were chosen to be slightly smaller than the inner diameters of the respective tubing.

The wheelchair-seated occupant was represented by a 50th percentile Hybrid III anthropomorphic testing device (ATD) (78.3 kg), while the crash pulse (25.8 km/h, 14 *g*) was as described in the proposed International Organization for Standardization (ISO)/Technical Committee (TC) 173 rear impact wheelchair standard [8]. **Figure 2** demonstrates that the sled deceleration pulse fell within the allowable ISO corridor (shaded region), conforming to ISO/TC 173.

In accordance with SAE J2249 ("Wheelchair tiedowns and occupant restraint systems"), the ATD was restrained using a surrogate, sled-mounted (vehicle-mounted), three-point lap and shoulder belt (LB and SB,

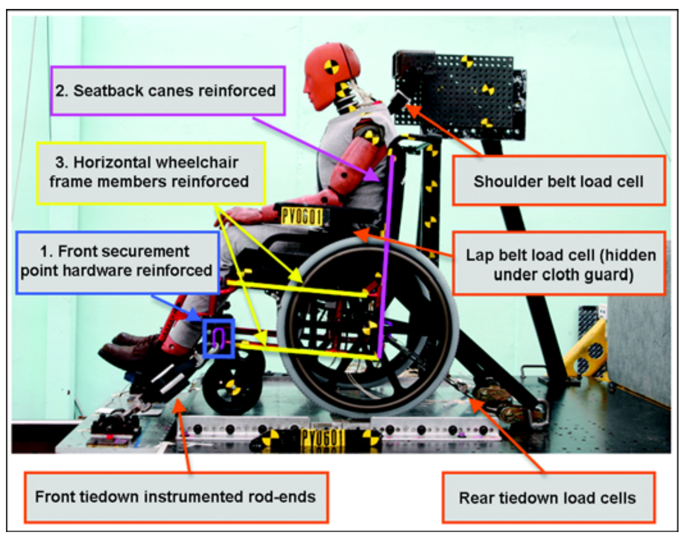

Figure 1.
Test setup showing key reinforced wheelchair components and load-cell placement. Three key wheelchair components were reinforced: 1. = front securement point hardware, 2. = seatback canes, and 3. = horizontal wheelchair frame members.

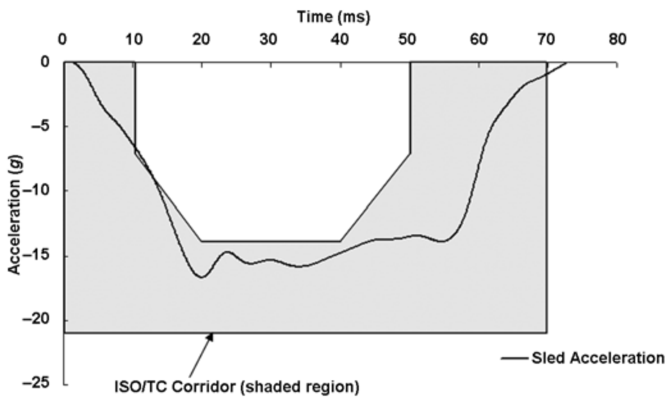

Figure 2.
Typical rear-impact sled deceleration pulse (solid heavy line) vs proposed International Organization for Standardization/Technical Committee (ISO/TC) 173 rear-impact wheelchair standard corridor (shaded region). Figure demonstrates that sled deceleration pulse falls within proposed ISO/TC 173 allowable corridor.

respectively) occupant restraint system (ORS), while the wheelchair was secured with surrogate, four-point strap-type tiedowns [9].

The tiedowns and ORS were both equipped with calibrated strain gauge-based load cells, which measured tension forces in the webbing during the impact sled test. Three-bar belt load cells (Denton Corp; Rochester Hills, Michigan) in the LB/SB and in the rear tiedowns measured the forces during the impact event, while instrumented rod-ends measured front tiedown loads. **Figure 1** shows the locations of load cells and instrumented rod-ends during setup. The instrumented rod-ends have a wider range than the three-bar belt load cells and can measure higher loads. Thus, the instrumented rod-ends were used to measure front tiedown loading because higher loads were expected in the front tiedowns than the rear tiedowns. WTORS-related measurements (**Figure 3**) from the test setup are shown in **Table 1**. The sampling rate and filtering were in accordance with the SAE J211 standard [10].

RESULTS

Figure 4 shows a side view frame sequence for a typical rear-impact test. The sequence begins at t = 0 ms and

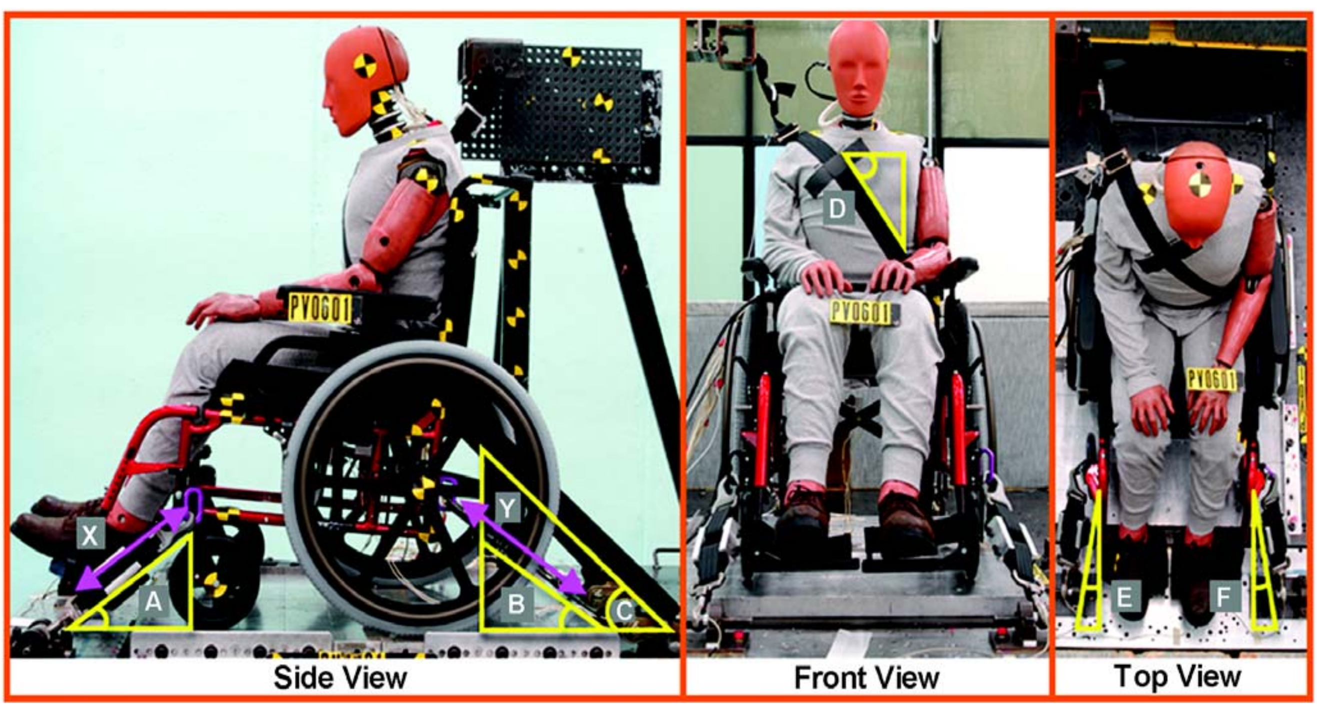

Figure 3.
Sled test setup measurements taken during test setup. A = front tiedown angle (side view), B = rear tiedown angle (side view), C = lap belt angle (side view), D = shoulder belt angle (front view), E & F = front tiedown angle (top view), X = front tiedown length, Y = rear tiedown length.

Table 1.
Sled test setup wheelchair tiedown and occupant restraint systems measurements.

Test	RTD Length (cm)	RTD Angle, Top View (°)	RTD Angle, Side View (°)	FTD Length (cm)	FTD Angle, Top View (°)	FTD Angle, Side View (°)	LB Angle, Side View (°)	SB Angle, Front View (°)
1	50	0	35	38	15	38	41	50
2	50	0	37	38	15	40	42	54
3	50	0	32	37	15	36	40	56

Note: Measurements corresponding to **Figure 3** are RTD length = Y, RTD angle (side view) = B, FTD length = X, FTD angle (top view) = E & F, FTD angle (side view) = A, LB angle (side view) = C, SB angle (front view) = D.
FTD = front tiedown, LB = lap belt, RTD = rear tiedown, SB = shoulder belt.

ends at t = 300 ms. After the deceleration pulse began, the ATD moved rearward and loaded the seatback, the front casters lifted off the sled platform (t = 120 ms), and the wheelchair rotated slightly rearward about the rear wheels. The ATD rearward head excursion peaked near 150 ms, followed by the rebound, during which the ATD began moving forward.

During the testing, front tiedown loads greatly exceeded rear tiedown loads, as was expected. These loads were relatively symmetric across left and right sides of the wheelchair (**Figure 5**). Front tiedowns were subjected to substantially higher forces during the initial 170 ms, (peaking at 75 ms, **Figure 5**) than during the remaining time period. These higher forces were noted because the front tiedowns serve as the primary means of securing the wheelchair and resisting its rearward motion during rear impact. The rear tiedowns experienced slightly higher loading than the front tiedowns after 170 ms in association with the rebound of the event (**Figure 5**). Peak tiedown loads for each impact test are provided in **Table 2**. The front tiedowns showed relatively symmetric peak loads, with the mean peak on the left side being 7,754 ± 84 N and right side 7,449 ± 270 N. Mean peak loading of the rear tiedowns was also relatively symmetric across the left (112 ± 105 N) and right (129 ± 126 N) sides.

Figure 6 shows the SB loading remained consistently negligible throughout the impact, while the LB loading was negligible only during the first 170 ms of the impact event. At t > 170 ms, the LB loading increased considerably, peaking near 225 ms and falling to zero again at t = 270 ms. Maximum ORS loading during each sled test is provided in **Table 2**. The mean peak SB loading (64 ± 4 N) was considered negligible compared with the mean peak LB load (1,630 ± 332 N). Test #1 failed to provide usable LB loading data because the LB slipped from the anchor point on the sled.

DISCUSSION

Interpreting Results

Rear tiedown loading during rear impact was found to be negligible compared with front tiedown loading. Since the rear tiedown load cells have a range of 13,345 N (3,000 lb), with an accuracy of 80 N (up to 6% of the full range), rear tiedown loading of 5 to 257 N was considered negligible. As shown in **Figure 5**, the front tiedowns were subjected to higher forces during the initial 170 ms of the crash pulse, because they served as the primary securement of the wheelchair and resisted its rearward motion (relative to the vehicle) during rear impact. Front tiedown loading increased as the ATD began loading the wheelchair seatback, transferring an additional load to the front tiedowns beyond the wheelchair inertial loading. After 170 ms, the front tiedown loads decreased and the rear tiedowns experienced negligible loading during the rebound phase of the event (**Figure 4**). The front tiedowns carried substantially higher loads during the impact, while the rear tiedowns were only loaded during wheelchair rebound. The ATD's rebound load was carried primarily by the LB. The negligible SB loads (**Table 2**) indicated that the SB was not involved in restraining the ATD during rebound.

This WTORS loading scenario was anticipated because of the forward-facing wheelchair setup and rear-impact dynamics. As shown in **Figure 4**, the posterior aspect of the ATD torso loaded the seatback, as the casters lifted off the sled platform and the wheelchair rotated slightly rearward about the rear wheels. This rotation resulted in extensive loading of the front tiedowns and negligible loading of the ORS during the primary event. The rebound phase followed the ATD's peak head excursion, during which the ATD began moving forward, loading the LB.

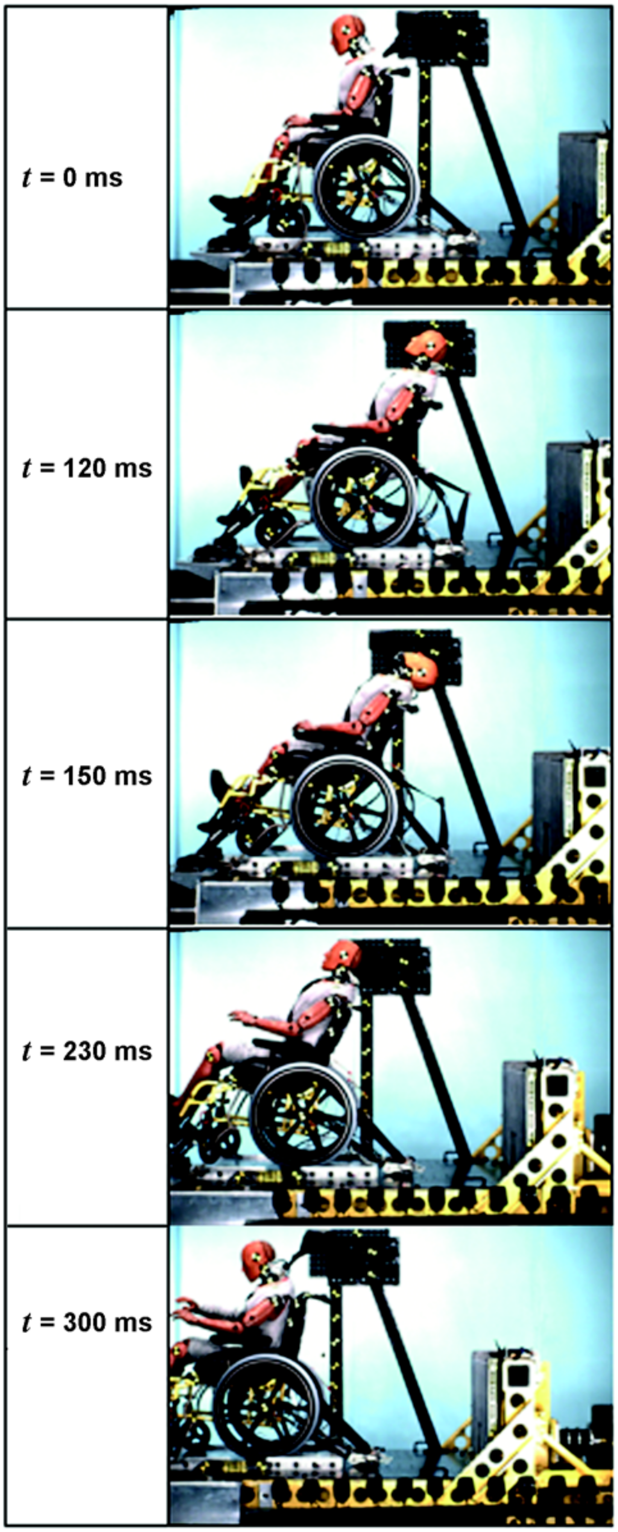

Figure 4.
Frame sequence of wheelchair-occupant response in typical rear-impact test. Click Here to Play Video

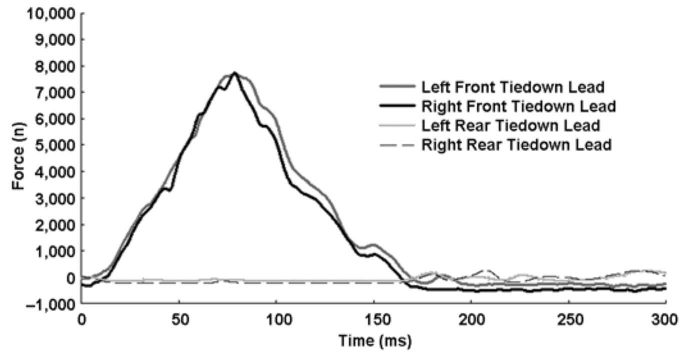

Figure 5.
Typical loading of four-point tiedown system during rear-impact sled test.

Comparison with Other Studies

It is important to compare our results with previously published WTORS loading data. **Table 3** shows a summary of peak WTORS loading from various studies.

Front Tiedowns

In a frontal impact, rear tiedowns limit forward excursion of the wheelchair, while the LB and SB limit forward excursion of the occupant. The ATD and wheelchair move rearward during the rebound phase of a frontal impact event. Because of these frontal impact dynamics, front tiedowns experience only minor loads in rebound that are considered relatively negligible compared with rear tiedown loads. In comparison with our study, Bertocci et al.'s computer simulation of front tiedown loads reached only 100 N under proper securement of a heavy power wheelchair (85 kg) in frontal impact when the rear wheelchair securement points were located at the same vertical height as the wheelchair center of gravity [11]. However, this previous study also showed that increasing the height of the rear securement point above the wheelchair center of gravity, inducing rearward wheelchair rotation, may increase front tiedown loads. In personal communication, UMTRI* reported measuring left-front tiedown and right-front tiedown peak loads of 456 N and 2,095 N, respectively, in a frontal impact test (48 km/h, 20 *g*) using a 33.2 kg manual

*Personal communication with Nichole Ritchie and Miriam Manary at University of Michigan Transportation Research Institute. January 4, 2007. Ann Arbor, MI.

Table 2.

Maximum wheelchair tiedown and occupant restraint systems loading (in newtons) during rear impact.

Test	LFTD Max	RFTD Max	LRTD Max	RRTD Max	LB Max	SB Max
1	7,851	7,415	13	124	4*	64
2	7,718	7,197	101	5	1,865	60
3	7,695	7,733	223	257	1,395	68
Mean Peak ± SD	7,754 ± 84	7,449 ± 270	112 ± 105	129 ± 126	1,630 ± 332	64 ± 4

*Force not measured accurately during sled test (LB slipped from anchor point); value not included in mean peak LB calculations.
LB = lap belt, LFTD = left front tiedown, LRTD = left rear tiedown, Max = maximum, RFTD = right front tiedown, RRTD = right rear tiedown, SB = shoulder belt, SD = standard deviation.

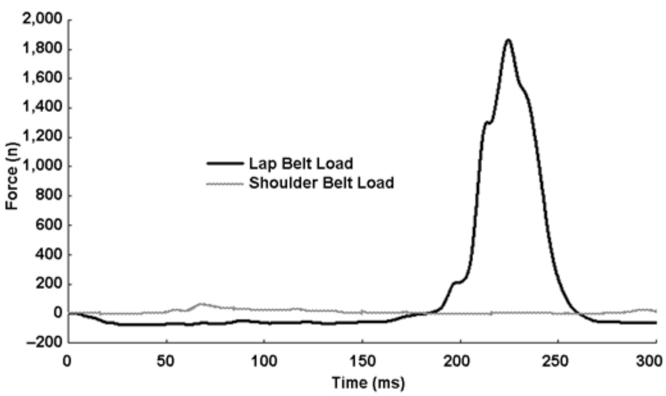

Figure 6.
Typical three-point occupant restraint system loading during rear-impact sled test.

wheelchair and a 50th percentile ATD. In this same UMTRI test, the wheelchair-anchored LB allowed for the SB to induce a lateral rotation of the ATD and wheelchair, resulting in asymmetrical front tiedown loads during rebound. Also of interest, the wheelchair used in this UMTRI test had a greater mass than the wheelchair used in our study (33.2 kg vs 25.1 kg). Despite these differences, the rear-impact dynamics in our study resulted in notably higher front tiedown loads of up to 7,851 N. These increased forces were noted because during rear impact, the wheelchair and ATD were facing opposite the direction of motion, requiring the front tiedowns to act as the primary securement during the impact. Despite the fact that the established ANSI/RESNA WC19 frontal impact crash pulse (48 km/h, 20 *g*) is more severe than the proposed rear-impact crash pulse (25.8 km/h, 14 *g*), the front tiedowns in our study were under much higher loads in rear impact than were reported during frontal impact rebound in other studies. Similar results were found by Fuhrman et al. in a rear impact (26 km/h, 11 *g*) study of a pediatric wheelchair with a seated Hybrid III 6-year-old with reported peak front tiedown loading of 4,600 N [12]. Front tiedown loading reported by Fuhrman et al. was lower than that found in our study because of lower wheelchair and ATD mass.

In some cases, the front tiedowns of commercial tiedowns are less robust. However, it is imperative that front tiedowns be designed to withstand loads associated with rear-impact collisions.

Rear Tiedowns

Rear tiedown loads have been reported by Leary and Bertocci to be approximately 6,230 N in a frontal crash of a comparable manual wheelchair with a seated 50th percentile ATD [13]. UMTRI and Bertocci et al. reported rear tiedown loads of 16,856 N and 21,033 N, respectively* [11]. These loads are substantially higher than the peak 257 N rear tiedown loads found in our rear-impact study. In frontal impact, the rear tiedowns serve as the primary means of securing the wheelchair as both the wheelchair and occupant move forward. Lower forces in the rear tiedowns in a rear impact are due to the majority of the load being carried by the front tiedowns. The minor loads on the rear tiedowns in rear impact are a result of the wheelchair rebound. Fuhrman et al. have reported peak rear tiedown loads of 1,600 N in their pediatric wheelchair rear-impact study [12]. Despite lower wheelchair and ATD mass, Fuhrman et al.'s loads were likely higher than the peak rear tiedown load of 257 N found in our study because the front wheelchair securement point in our study deformed substantially. The securement point in our study was offset by approximately 6 cm from the wheelchair frame. As the front tiedown load was transmitted through the front securement point to the wheelchair frame, the front securement point and bolts

*Personal communication with Nichole Ritchie and Miriam Manary at University of Michigan Transportation Research Institute. January 4, 2007. Ann Arbor, MI.

Table 3.
Comparison of wheelchair tiedown and occupant restraint systems (WTORS) loading in our study to published WTORS loading from previous studies.

Study	Type of Study	Impact Direction	Impact Severity	Wheelchair Type	Wheelchair Mass (kg)	ATD Mass (kg)	Peak FTD Load Per TD (N)	Peak RTD Load Per TD (N)	Peak SB Load (N)	Peak LB Load (N)
Bertocci et al. [1]	Computer Simulation	Frontal Impact	48 km/h, 20 *g*	Adult Power	85.0	78.3	100	21,033	NR	8,273
Leary & Bertocci [2]	Computer Simulation	Frontal Impact	48 km/h, 20 *g*	Adult Manual	20.9	78.3	NR	6,228	9,786	15,569
UMTRI [3]	Sled Test	Frontal Impact	48 km/h, 20 *g*	Adult Manual	33.2	78.3	2,095	16,856	10,800	5,658
Fuhrman et al. [4]	Sled Test	Rear Impact	26 km/h, 11 *g*	Pediatric Manual	17.9	23.5	4,800	1,900	131	1,267
Current Study	Sled Test	Rear Impact	25.8 km/h, 14 *g*	Adult Manual	25.1	78.3	7,851	257	68	1,865

1. Bertocci GE, Hobson DA, Digges KH. Development of transportable wheelchair design criteria using computer crash simulation. IEEE Trans Rehabil Eng. 1996;4(3):171–81. [PMID: 8800220]
2. Leary A, Bertocci GE. Design criteria for manual wheelchairs used as motor vehicle seats using computer simulation. Proceedings of the RESNA Annual Conference; 2001 Jun; Reno, NV. Arlington (VA): RESNA; 2001.
3. Personal communication with Nichole Ritchie and Miriam Manary at University of Michigan Transportation Research Institute (UMTRI); Jan 4, 2007. Ann Arbor, MI.
4. Fuhrman SI, Karg P, Bertocci G. Characterization of pediatric wheelchair kinematics and wheelchair tiedown and occupant restraint system loading during rear impact. Med Eng Phys. Epub 2009 Apr 22. [PMID: 19398366]

ATD = anthropomorphic testing device, FTD = front TD, LB = lap belt, NR = not recorded, RTD = rear TD, SB = shoulder belt, TD = tiedown.

deformed, bending beyond their elastic limits. While the front securement point deformed in the primary phase of the rear-impact event, energy from the impact was absorbed. This absorption resulted in a less severe rebound of the ATD and wheelchair in our study, with reduced rear tiedown loading, despite the larger mass compared with Fuhrman et al.'s study.

Occupant Restraints

Bertocci et al. have reported peak LB loading of 8,273 N [11], and Leary and Bertocci have reported SB peak loads of 9,786 N and LB peak loads of 15,569 N [13]. UMTRI reported peak SB and peak LB loading of 10,800 N and 5,658 N, respectively. These ORS loads in frontal impact are substantially higher than the peak LB load of 1,865 N and peak SB load of 68 N found in our rear-impact study. These differences are because in frontal impact, the LB and SB are the primary means of restraining the occupant. In our rear-impact study, the wheelchair seatback resists the excursion of the ATD, ultimately transferring this load from the seatback through the wheelchair frame to the front tiedowns; the ORS is only loaded in rebound. Fuhrman et al. have reported similar results to those found in our study, with negligible peak SB loading (131 N) and LB loading of 1,267 N [12]. Since Fuhrman et al. used a Hybrid III 6-year-old ATD with lower mass, the reported peak LB load was slightly lower than the 1,865 N load found in our study. However, since the wheelchair and occupant were subjected to rear-impact dynamics in both Fuhrman et al.'s and our study, the ORS was loaded only in rebound.

Importance of Findings

This study confirmed that WTORS forces differ greatly between the frontal and rear-impact scenarios and provided a quantitative comparison of WTORS loading in frontal impact sled tests and computer simulations. It is critical that both tiedown and wheelchair manufacturers become aware of these differences so that they can design safer and more effective securement systems, as well as wheelchair securement points and seatbacks on ANSI/RESNA WC19 compliant wheelchairs that are appropriate for both frontal and rear-impact events. Failure to do so could lead to tiedown failure, securement point failure, and seatback failure in rear impact, as has already been demonstrated [3].

Limitations

It is important to note that the test protocol and crash pulse used in this study were based upon a proposed ISO rear impact wheelchair standard [8] that has not yet been adopted by ISO. A further limitation of this study is that one type of manual wheelchair make and model was used for all tests; other manual wheelchairs may generate different WTORS loading. It is also important to note that the wheelchair used in our study was reinforced, making the frame and seatback stiffer and thereby likely affecting WTORS loading. Furthermore, a power wheelchair, having higher mass, would be anticipated to produce higher WTORS loading. Other variables that may affect WTORS loads include wheelchair securement point location and geometry, ATD mass, and crash pulse severity.

CONCLUSIONS

In a frontal impact, rear tiedowns limit forward movement of the wheelchair, while the LB and SB limit forward excursion of the occupant. During rear impact, the front tiedowns provide the primary securement of the wheelchair and the seatback acts to resist excursion of the occupant. Our study of an adult manual wheelchair with a seated 50th percentile ATD found front tiedown loading in rear impact to be substantially higher (7,197–7,851 N per front tiedown) than previously reported front tiedown loads in frontal impact. Rear tiedown loads in our study were negligible (maximum 5–257). The ORS loads in our rear impact study also differed from those found in other studies of frontal impact, with peak LB loads of up 1,865 N and negligible SB loads (maximum 60–68 N). These differences in loading must be considered in the design of WTORS and wheelchairs to assure wheelchair user safety in both frontal and rear impacts.

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Study concept and design: Z. Salipur, G. Bertocci.
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Analysis and interpretation of data: Z. Salipur, G. Bertocci.
Drafting of manuscript: Z. Salipur, G. Bertocci.
Statistical analysis: Z. Salipur.
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