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Evaluation of wheelchair back support crashworthiness: combination wheelchair back support surfaces and attachment hardware

DongRan Ha, BS; Gina Bertocci, PhD; Ernest Deemer, BS; Linda van Roosmalen, MS; Patricia Karg, MS
Injury Risk Assessment and Prevention (iRAP) Laboratory, Department of Rehabilitation Science & Technology, University of Pittsburgh, Pittsburgh, PA 15260

Abstract—Automotive seats are tested for compliance with federal motor vehicle safety standards (FMVSS) to assure safety during impact. Many wheelchair users rely upon their wheelchairs to serve as vehicle seats. However, the crashworthiness of these wheelchairs during impact is often unknown. This study evaluated the crashworthiness of five combinations of wheelchair back support surfaces and attachment hardware using a static test procedure simulating crash loading conditions. The crashworthiness was tested by applying a simulated rearward load to each seat-back system. The magnitude of the applied load was established through computer simulation and biodynamic calculations. None of the five tested wheelchair back supports withstood the simulated crash loads. All failures were associated with attachment hardware.

Key words: *wheelchair back support, wheelchair crashworthiness, wheelchair injury prevention, wheelchair safety, wheelchair testing.*

BACKGROUND

Manufacturers of automotive seats are required to perform extensive testing to assure that their production vehicle meets government crashworthiness and occupant protection regulations as described by Federal Motor Vehicle Safety Standards (FMVSS; 1,2). Seats and hardware have to withstand certain loads during a crash and must provide support for the occupant under impact loading and during rebound. Wheelchair users who cannot transfer to vehicle seats use their wheelchairs as vehicle seats while they travel. However, the level of protection that wheelchair seating systems provide under impact is, in many cases, unknown. Although ANSI/RESNA WC-19 evaluates wheelchair crashworthiness, substitute seating systems are often added as after-market products and will not be sled tested (3). A typical wheelchair seating system (WCSS) consists of a separate seat and back surface with cushions mounted onto the wheelchair frame using attachment hardware (**Figure 1**). The integrity of supporting surfaces and attachment hardware must be maintained during a crash. Therefore, a test to evaluate and predict wheelchair seating surface and attachment hardware crashworthiness, independent of the wheelchair frame, would be useful for seating system manufacturers. This study proposes a static test method and applies this method to evaluate five commercial wheelchair back support surfaces and their associated attachment hardware: Jay2 Deep Contour Back, Jay2 Back Tall, Jay Fit Back System, Personal Back, and Sit Rite Back.

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Address all correspondence and requests for reprints to: Gina E. Bertocci, PhD, PE, University of Pittsburgh, Department of Rehabilitation Science and Technology, 5034 Forbes Tower, Pittsburgh, PA 15260; email: ginaber@pitt.edu.

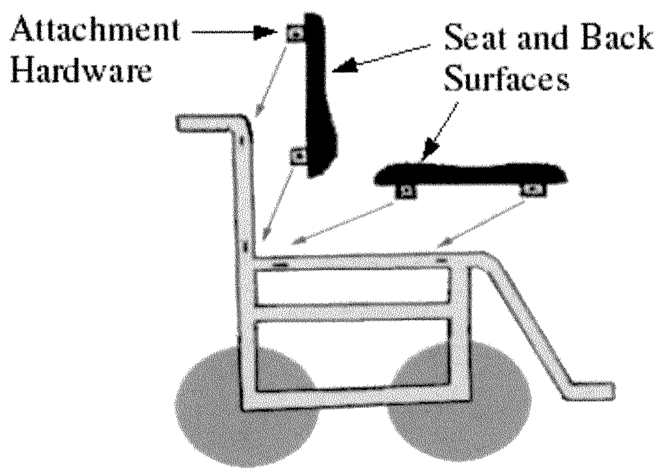

Figure 1.
Common WCSS Configuration.

METHODS

Development of Test Criteria

Two loading conditions that wheelchair back supports may be exposed to in transport are rebound loads associated with frontal impacts and loads encountered during rear impacts. In developing test criteria the worse-case loading scenario was chosen.

Rear impact loads were derived following FMVSS 207 test criterion that applies a 20-g static load to the seat-back portion of seating systems. This load is applied in the forward and rearward direction to the center of gravity of the seat. However, the current FMVSS 207 test protocol derives the 20-g load by considering only the weight of the seating system, and does not include the weight of the occupant upper torso. The inclusion of occupant load in FMVSS 207 test methods has been addressed recently by a number of researchers (4–7). The study done by Thomson et al. showed that a 50th-percentile male occupant exerts roughly an 11,408 in-lb moment on a stiff seatback during a 4g/8.7mph rear impact (5); 3.5 times greater than that calculated using the FMVSS 207 protocol. This study illustrates that even during a low impact situation, inclusion of occupant loading in formulating seat-back loading criteria is critical. In a petition to NHTSA to modify FMVSS 207, Saczalski suggested that seat-back loads be based upon the weight of the seat plus the weight of a 95th-percentile male occupant at a 30-g crash severity (6). Saczalski also suggested that the FMVSS 207 seat-back moment test be increased from 3,300 in-lb to 56,000 in-lb to account for upper torso loading on the seat back. It is also important to note that wheelchair seating systems are significantly lighter than motor vehicle seats and would result in unrealistically low test loads if the current FMVSS 207 protocol were followed. Therefore, although FMVSS 207 utilizes the weight of the seat times 20 g to derive the applied test load, the sum of the occupant upper torso and seat weights times 20 g is more appropriate and is used to derive the test criteria in our study.

Accordingly, rear impact loading was calculated as 20 $\times$ (weight of the upper torso of a 50th-percentile male +weight of each wheelchair back support). Since the weight of the back support specimens were similar (4.5 lb–5.5 lb), and the weight of the 50th-percentile male upper torso is constant (113 lb), rear impact equivalent loading ranged from 2,350 lb to 2,370 lb (8,9).

A review of previously conducted wheelchair sled testing revealed no record of back support loads. Therefore, rebound loads associated with frontal impact were determined from computer crash simulations. Using a previously validated 20g/30mph frontal-impact wheelchair-occupant model, peak back support loading associated with rebound of a 50th-percentile male was found to be approximately 2,280 lb (10).

Since rear impact loading was slightly higher, the back support loading criterion for the protocol was based upon rear impact conditions of 2,400 lb.

Test Setup

A rigid test fixture was developed to mount the wheelchair back support surface (WBSS) with attachment hardware (AH) to the Instron testing machine (**Figure 2**). Two 1-inch diameter solid rods of the test fixture simulated the wheelchair back vertical support members. Rods were spaced 18 inches apart, representing a

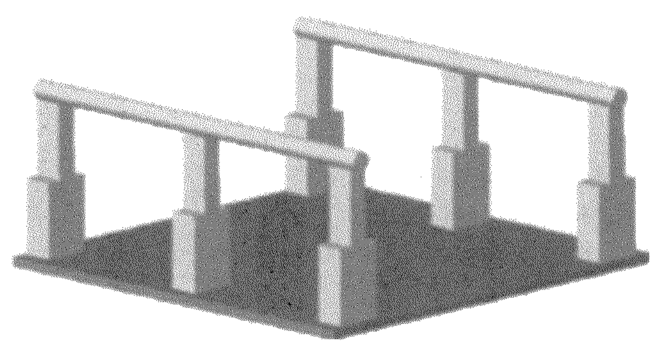

Figure 2.
Surrogate wheelchair frame test fixture.

common adult wheelchair back frame. The loads applied to the WBSS and AH were generated using the Instron Series 4204 loading machine, which is designed to test materials in either tension or compression. Loads were transmitted to the back supports using the upper torso (back) unit of the ISO 7176-07 test dummy, a reference loader gage (RLG), which was "designed to simulate the dimensions and mass distribution of the human body" (**Figure 3**; reference 11).

The test procedure consisted of the following steps (**Figure 4**). Wheelchair back support surfaces were mounted to the rods of the test fixture following manufacturers' instructions and using manufacturer-provided hardware. The back unit of the RLG, representing the upper torso, was placed on top of the back support surface. Using the Instron testing device, a downward force was applied to the back unit of RLG at its center of gravity. The load was applied at an Instron cross-head speed of 20 in/min. Barring failure, the load was held for 5 seconds, then released at 20 in/min. The target load and cross-head speed were programmed into the Instron computer. Instron cross-head position and the applied load were recorded during the test at 4 Hz. Since the cross head was in contact with the back support surface, the back support surface deflection was quantified through the position of the cross head. Two specimens of each product were tested.

RESULTS

Table 1 indicates the main reason for failure and **Table 2** indicates the failure load and stiffness of each wheelchair back support. Stiffness of back support was calculated from the slope of each load versus deflection curve. This information was calculated for use in computer crash simulation models.

All five wheelchair back supports failed to withstand the test criterion load because of attachment hardware failures. Failures are shown from **Figure 5** to **Figure 9**. As shown, hardware failures included severe deformation of metal components, as well as fracture of plastic components. **Figure 10** through **Figure 14** show the load *versus* deflection curves of the five tested wheelchair back supports; Xs indicate the point of failure. Four out of five tested back supports failed at loads less than 50 percent of the targeted load of 2,400 lb. The J2 Tall withstood the highest load, 1,468 lb, and the Personal Back failed at the lowest load, 402 lb. Back support stiffness ranged from 103 lb/in to 443 lb/in.

DISCUSSION

Each of the tested back support surface and attachment hardware combinations failed at levels below those expected in a rear impact or rebound phase of a frontal impact. Despite testing protocol limitations associated with static loading, it is of relevance that all but one commercial wheelchair back support system failed at loads less than 50 percent of that which may be experienced in rebound or rear impact.

Two contradictory philosophies in occupant protection and seat-back design continue to be investigated: stiff seat back *versus* yielding seat back. Studies by Strother and James, and Warner et al. concluded that controlled yielding seat backs are more effective in reducing rear impact injury risk (12,13). Strother and James found that rigid seat backs resulted in increased risk of whiplash

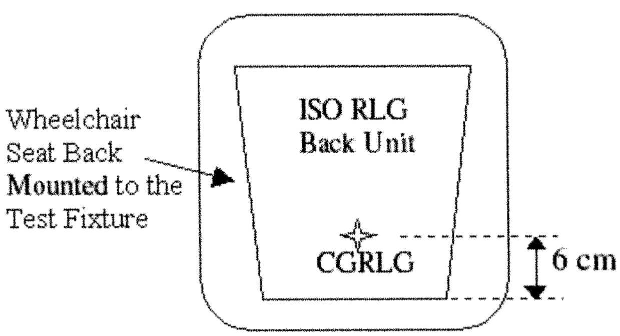

Figure 3.
Top view of the load application point on the ISO Back Unit.

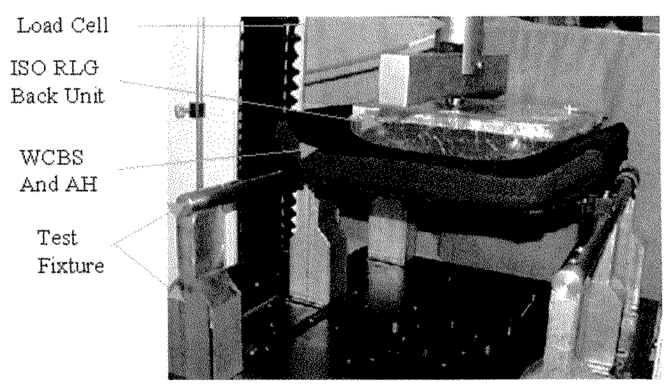

Figure 4.
Test set up.

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Table 1.

Manufacturer	Test Seat Back		Failure Description
Sunrise Medical	J2 Deep Contour	Test 1	upper hardware: left side severe deformation lower hardware: left side released from retention slot
		Test 2	upper hardware: right side severe deformation lower hardware: left side released from retention slot
Sunrise Medical	J2 Back Tall	Test 1	upper hardware: both sides severe deformation lower hardware: left side released from retention slot
		Test 2	lower hardware: both sides released from retention slots (knobs at the end of lower hardware missing--defect)
Sunrise Medical	Jay Fit Back	Test 1	lower hardware: both side pins released from retention slots
		Test 2	lower hardware: both side pins released from retention slots
Invacare	Personal Back	Test 1	lower hardware: plastic part of the hardware at both sides fractured and released from retention slots
		Test 2	lower hardware: metal part of the hardware at both sides severely bent and released from retention slots
Metro Medical	Sit-Rite	Test 1	all four pieces of hardware severely deformed; lower hardware slipped free
		Test 2	all four pieces of hardware severely deformed

Table 2.

Manufacturer	Tested Seat Back/Hardware	Failure Load Test 1 (lb)	Failure Load Test 2 (lb)	Stiffness Test 1 (lb/in)	Stiffness Test 2 (lb/in)
Sunrise Medical	J2 Deep Contour	984	835	443	274
Sunrise Medical	J2 Back Tall	1468	296	366	103
Sunrise Medical	Jay Fit Back	507	773	137	209
Invacare	Personal Back	402	406	126	106
Metro Medical	Sit-Rite	1113	1085	233	254

injuries. However, according to Rake and Boehm, the biomechanical injury tolerance data generated from volunteers (14) showed that human bodies could withstand forces much higher than those likely to occur during rear impacts when they were "supported in a rigid seat with proper cushions and padding" (7). This contradiction in findings requires that optimal seat-back stiffness be investigated further so that the proper balance in stiffness of vehicle and wheelchair seat backs can be achieved.

In all cases, back support attachment hardware was the source of failure in this study. Many of the back supports utilized drop hook type attachment hardware that

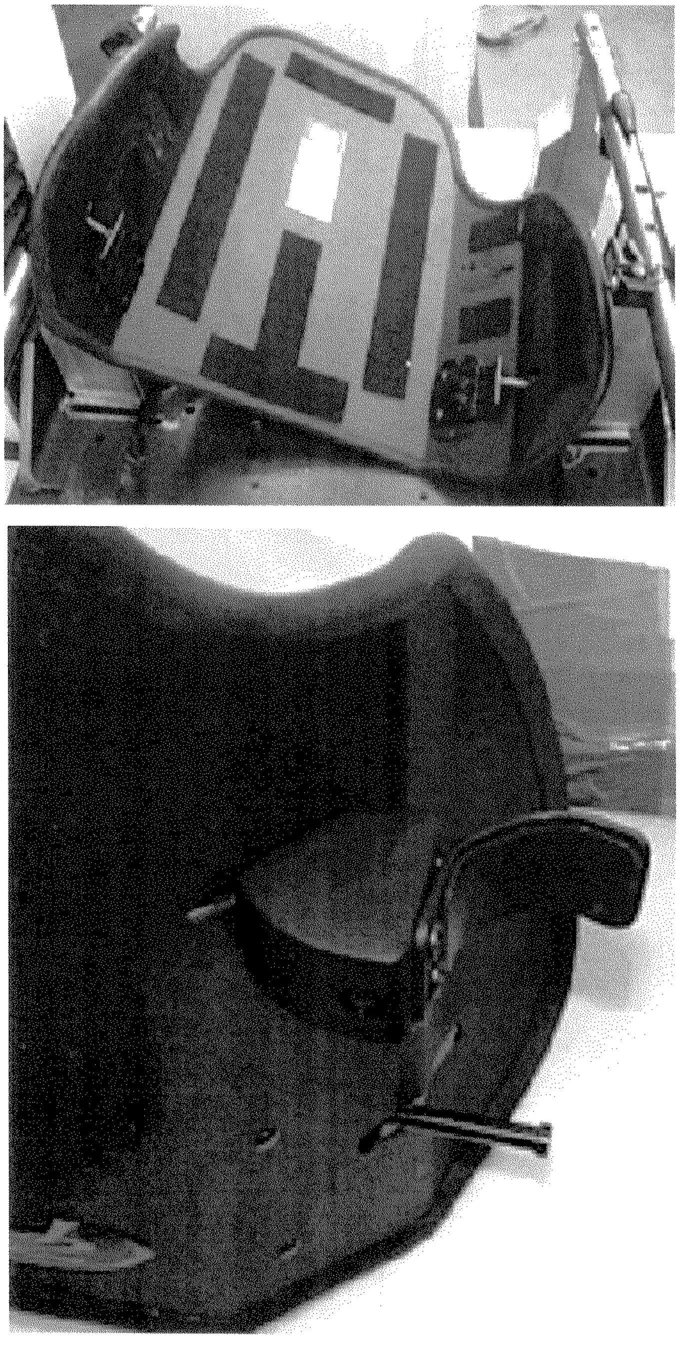

Figure 5.
Failure of J2 Deep Contour (**a**) Test 1 and (**b**) Test 2.

deformed by straightening, allowing the back support to slip free of the test fixture rail. In an actual wheelchair arrangement, such a failure would equate to the back support slipping past the vertical wheelchair back support members when loaded by the upper torso during rebound or rear impact. This type of failure could lead to excessive

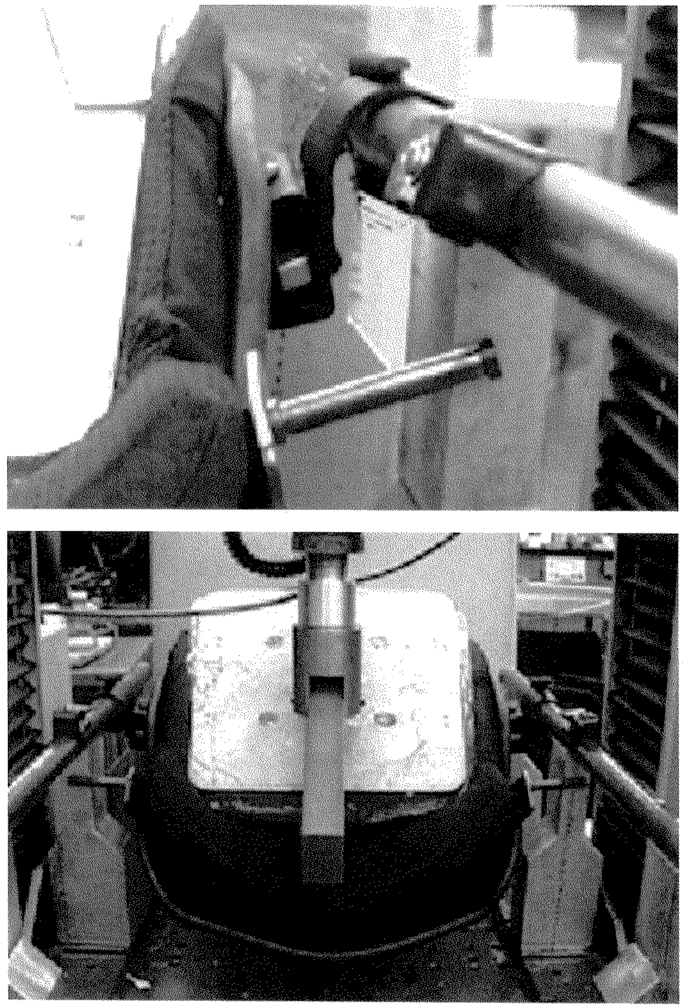

Figure 6.
Failure of J2 Back Tall (**a**) Test 1 and (**b**) Test 2.

rearward occupant excursion. Excessive rearward excursion associated with back support failure increases the risk of secondary head impact with interior vehicle surfaces (13). Back support failure has also been shown to be associated with increased risk of cervical spine injury, as well as increased risk of ejection from the seat, because occupant restraints are rendered ineffective (6,15). The ANSI/RESNA WC-19 Wheelchair Used as Motor Vehicle Seats Standard (3) attempts to capture wheelchair back support failure or excessive yielding that may occur during the rebound phase of a frontal impact. WC-19 limits rear head excursion to 15.7 inches as a part of the proposed frontal impact sled test requirements.

It is important to note that the tested wheelchair back support surfaces and attachment hardware were designed for normal mobility and may not necessarily have been

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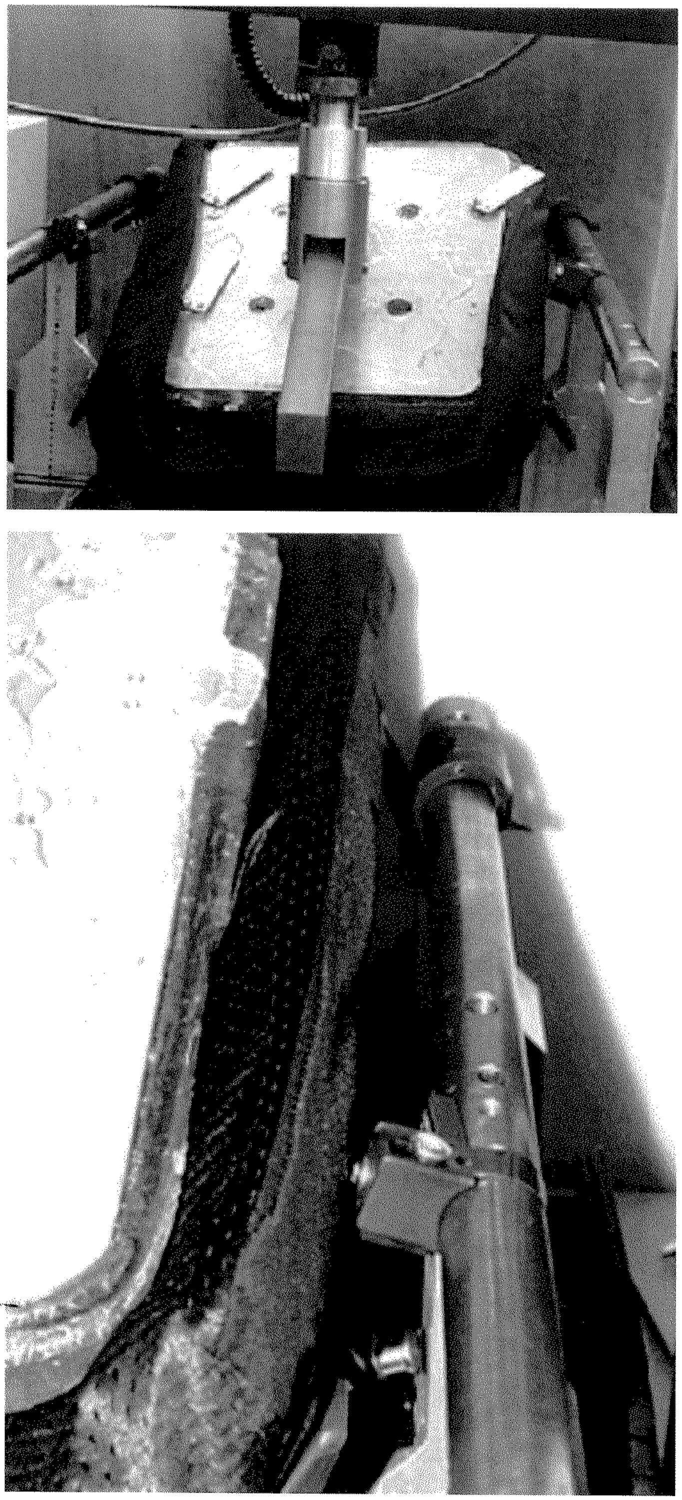

Figure 7.
Failure of J2 Jay Fit Back (**a**) Test 1 and (**b**) Test 2.

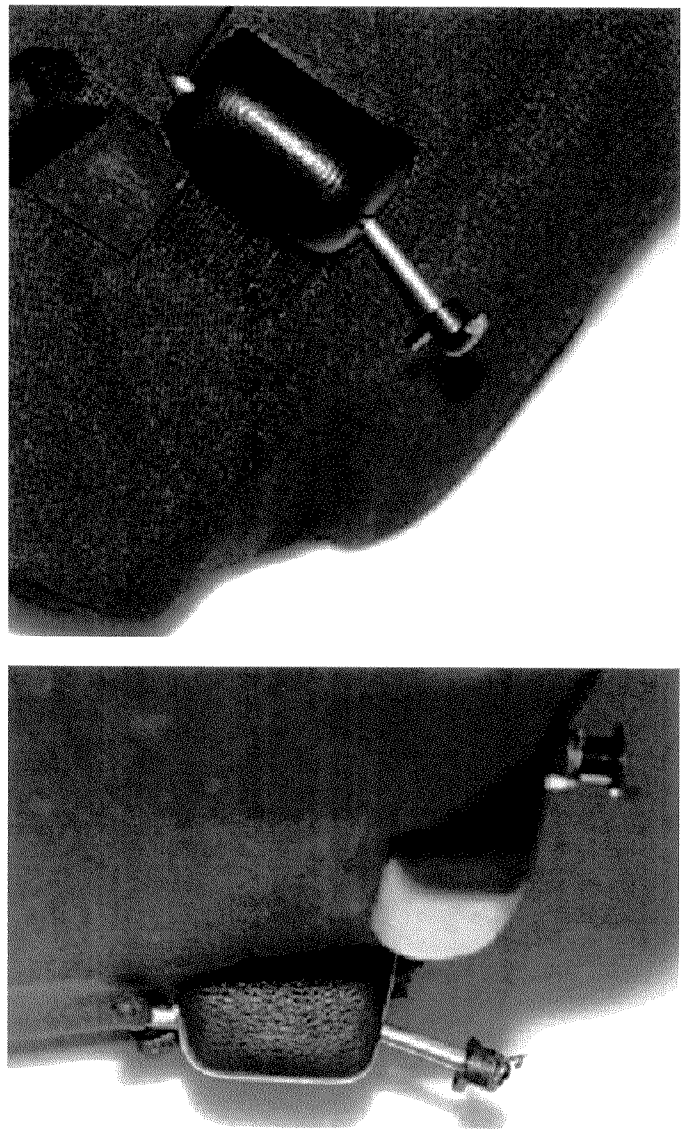

Figure 8.
Failure of Personal Back (**a**) Test 1 and (**b**) Test 2.

designed to be used as seats in motor vehicles. Many commercial wheelchair seating systems were designed for users who can transfer from their wheelchair to vehicle seats and provide the user a means for easy detachment of components for stowing. Accordingly, manufacturers have designed "quick release" attachment hardware to aid wheelchair users in detaching seating support surfaces from the wheelchair frame to allow for folding of the wheelchair. However, attachment hardware that provides for quick release and does not provide full capture of the wheelchair frame may not perform well under crash conditions. Since in some cases the same wheelchair user may transfer to a motor vehicle seat in one transport mode (e.g. private transport), but may choose to remain seated in their wheelchair in another transportation setting (e.g. public transport), it is important that wheelchair seating

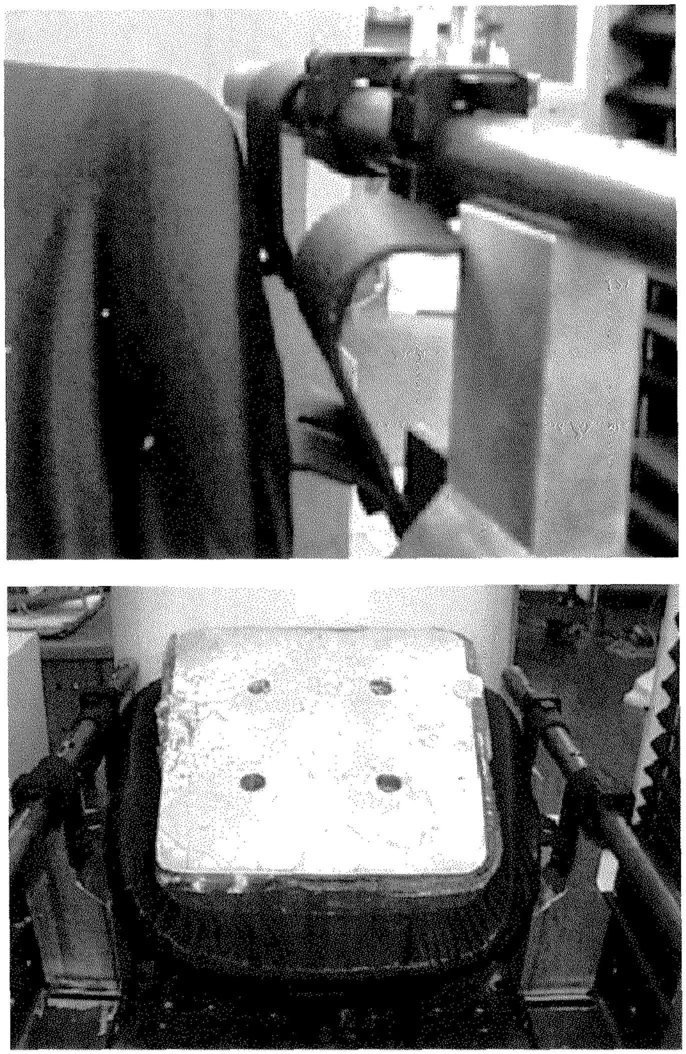

Figure 9.
Failure of Sit-Rite Back (a) Test 1 and (b) Test 2.

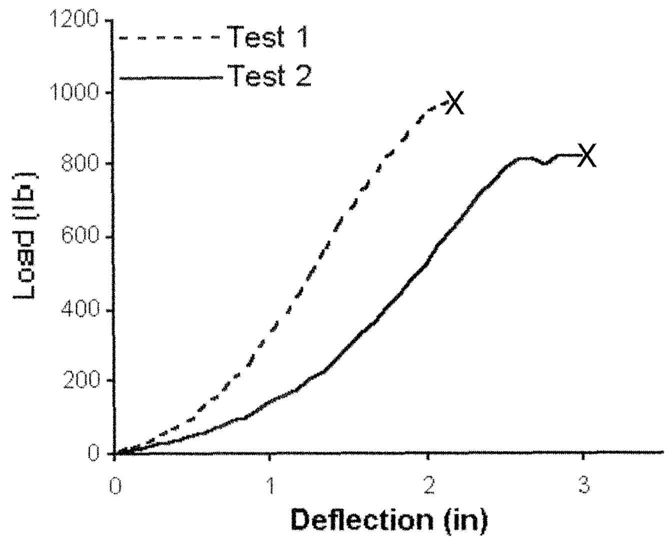

Figure 10.
Load vs. Deflection of J2 Deep Contour— "X" indicates failure.

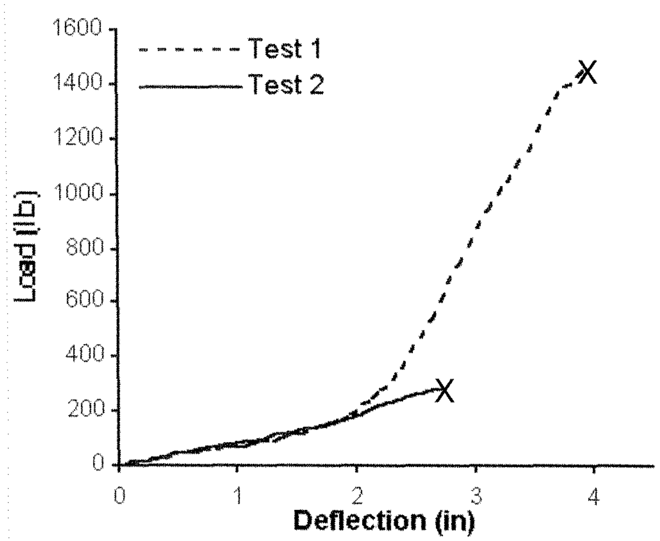

Figure 11.
Load vs. Deflection of J2 Back Tall— "X" indicates failure.

manufacturers consider both needs. Manufacturers are encouraged to consider revised seating design criteria that include both the need for ease of component detachment, as well as loading conditions associated with using the wheelchair seating system in a motor vehicle.

The test protocol used in this study provides a low-cost method of previewing seating surface and attachment hardware crash integrity. However, it is important to note that the loading conditions utilized in the protocol are statically applied, while loading conditions associated with a crash are applied dynamically. As a next step, the proposed static testing protocol will be evaluated to assess similarity with dynamic loading in a sled impact test. It should also be noted, however, that a single sled test represents but only one seating/wheelchair configuration—one which may not necessarily lead to maximum loading that may be encountered in an actual wheelchair transportation scenario. For example, the location of rear securement points, which has previously been shown to influence seat loads in a crash, may be positioned during the sled test so as to produce less than maximum seat loads. A different securement point configuration, resulting from combining the seating system with a different wheelchair frame in the field, may produce seat loads that are higher than those associated with a single sled test.

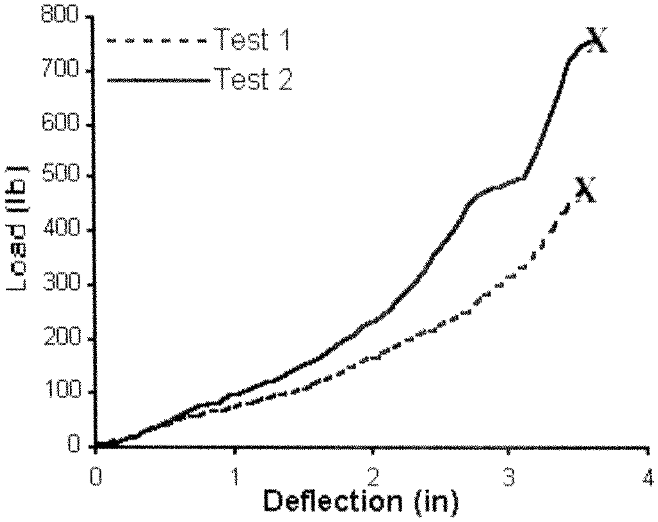

Figure 12.
Load vs. Deflection of Jay Fit Back— "X" indicates failure.

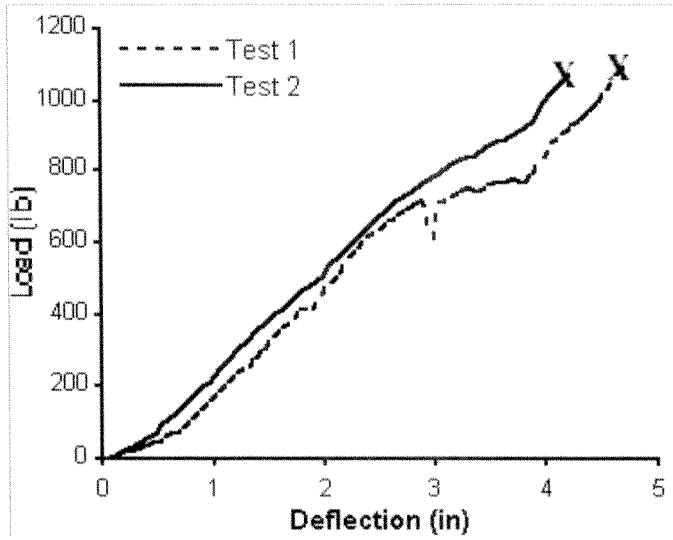

Figure 14.
Load vs. Deflection of Sit-Rite Back— "X" indicates failure.

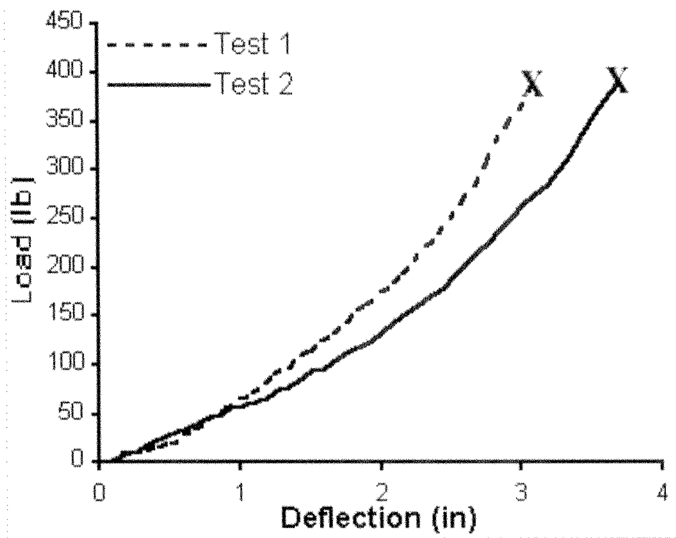

Figure 13.
Load vs. Deflection of Personal Back— "X" indicates failure.

In contrast to a single sled test, the static test procedure used in this study attempts to evaluate seating performance under worst-case loading conditions—an approach that should be followed in the design of all safety products. Another benefit of the proposed test protocol is that it provides seating manufacturers with a means of isolating the performance of their product, independent of the numerous wheelchair frames upon which it may be mounted. Such low-cost static testing can also aid manufacturers in the design of crash-safe seating components and systems. To provide the highest level of safety, seating manufacturers would utilize a combination of static testing and dynamic testing. Upon passing static testing to peak expected loading, manufacturers would then test their product under dynamic sled testing conditions with the actual wheelchair frame intended to be used with the seating system. Unfortunately, many seating systems are provided as replacement products after the wheelchair has been in the field, making it impossible to evaluate the combination wheelchair and seating system. In these after-market cases, evaluation of seating system performance independent of the wheelchair is crucial to wheelchair-user safety.

CONCLUSIONS

The results of this study show that none of the tested commercially available combinations of wheelchair back support surfaces and attachment hardware withstood the forces that may be encountered during rear impact or rebound associated with a 20g/30mph frontal impact. Results of testing show that all but one back support system failed at loads that are less than 50 percent of back support loading that may be experienced during rebound or rear impact. While compliance with this low-cost static load test would not necessarily imply a crash-proof wheelchair seating system, it does serve as a first step towards evaluating safety for the use of wheelchairs as motor vehicle seats. Future work will focus on validating the proposed static test methods to assure dynamic impact test similarity. Additional efforts will also seek to evaluate other wheelchair seating components.

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