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Development of frontal impact crashworthy wheelchair seating design criteria using computer simulation

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Abstract—When designing wheelchairs for use as motor vehicle seats, special design criteria must be followed to assure the crash safety of the wheelchair user. Failure of seating system components under crash loading conditions could lead to serious injury or fatality. In this study, seat and seat-back loading in a frontal crash are explored using computer simulation techniques. A previously validated simulation model consisting of a powerbase wheelchair and a seated 50th-percentile male test dummy subjected to a 20g/30mph frontal impact were used for the study. Since such a wide range of seating systems are available, parametric analyses were conducted to evaluate the influence of surface stiffness and seat-back angle on wheelchair seat and back loading. Seat loading varied with stiffness, ranging from 819–3,273 lb., while seat-back loading was found to be between 1,427–2,691 lb., depending upon back stiffness and recline angle.

Key words: *wheelchair crashworthiness, wheelchair design, wheelchair injury prevention, wheelchair safety, wheelchair seating*

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INTRODUCTION

Motor vehicle seat designs incorporate numerous features that protect an occupant in a crash. For example, seat system strength, stiffness, energy absorbance, and position have been shown to have a direct impact on occupant kinematics, and in particular on submarining risk (1–4). (Submarining occurs when the pelvic restraint slips upward over the iliac crests, loading the soft abdominal tissue.) Motor vehicle seat strength is assessed through both static testing in FMVSS 207, Seating Systems, and dynamic testing in FMVSS 208, Occupant Crash Protection (5,6). FMVSS 207 testing focuses on seat-to-back and seat-to-vehicle anchorage strength, while FMVSS 208 indirectly assesses seat performance through evaluation of occupant injury risk indicators.

Wheelchair users who are unable to transfer to a motor vehicle seat must rely upon their wheelchair to provide a stable support surface and occupant protection in a motor vehicle crash. Unfortunately, many wheelchairs have not been designed with the intention to serve as a motor vehicle seat. Crash conditions pose more severe loads on wheelchair components than typical mobility conditions (7). ANSI/RESNA WC-19: Wheelchairs Used as Seats in Motor Vehicles addresses the crashworthiness of wheelchairs, assessing complete wheelchair systems

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through a variety of tests including 20g/30mph dynamic frontal impact testing (19).

Early testing of wheelchairs to 20g frontal impact conditions has indicated that some seating system designs may be problematic in a crash, providing less than adequate occupant support (8). Seating support surface failures and excessive seating attachment hardware deformation have been seen in a number of wheelchair sled tests. Support surface failures have included both seat-back failure during the rebound phase of the impact event and seat-surface failure associated with downward loading during impact.

Although ANSI/RESNA WC-19 provides a major advance in the evaluation of wheelchairs used in motor vehicle transportation, there are service delivery scenarios that may circumvent the advantages offered through complete wheelchair system testing. A common scenario may include a wheelchair frame or base purchased by a rehabilitation technology provider who adds an after-market seating system to the wheelchair base to provide a complete system. In this case, unless the wheelchair and seating system manufacturer have previously tested the specific combination of wheelchair base and seating system, previous ANSI/RESNA WC-19 testing of the wheelchair base is void. Additionally, specific seating attachment hardware and associated installation instructions would also need to be indicated for this specific wheelchair-seat combination.

Another service delivery scenario that exists is that in which the clinician/rehabilitation technology provider customizes a seating system (e.g. foam-in-place) for an individual wheelchair user. Again, mounting such a seating system to an ANSI/RESNA WC-19-approved wheelchair frame/base provides no guarantee as to how the newly combined system will perform in a crash.

To address this need, the RESNA Subcommittee on Wheelchairs and Transportation is in the process of defining a standard that will specify design and testing requirements for after-market seating systems. As a first step in developing suitable test protocols, crashworthy design criteria must be established for wheelchair seating systems. This type of information can be drawn from various sources: current automotive legislation, loads measured during sled impact testing of wheelchairs and validated computer simulation models of wheelchair-occupant systems subjected to impact conditions. Computer crash simulation models offer the advantage of being able to explore the influence of a specific design parameter on seating system loads, which would otherwise be costly to assess through experimental testing. This study relies upon computer crash simulations and parametric studies to provide wheelchair crashworthy seating system design criteria suitable for 20g frontal impact conditions. A survey of the literature and a review of previously conducted sled tests that have attempted to measure seating system loads are also included. In keeping with the initial goal of the RESNA Subcommittee, this study focuses on seating system loading associated with frontal impact conditions and its associated rebound phase.

Wheelchair seat loading associated with frontal impact occurs when the occupant's inertial forces cause forward movement, which is resisted by the pelvic restraint and seat. The pelvic restraint opposes occupant forward excursion through an opposing force in the downward direction, driving the occupant downward into the seat (**Figure 1**). The occupant weight, severity of the crash, and location of rear securement attachment to the wheelchair are factors that influence seating system loading. The degree of seat incline, seat friction, and seat stiffness will also affect the load applied to the seat surface. Seat-back loading also occurs in frontal impact. During the rebound phase of frontal impact the occupant applies a rearward load on the seat-back surface. Again, characteristics such as seat-back stiffness and seat-back angle affect the loading profile of the seat back. To control wheelchair user injury risk in a motor vehicle crash, seat and back support surfaces, along with attachment hardware, must be designed to withstand the large dynamic forces associated with crash conditions. As an initial step in defining crashworthy design criteria, this study explores the range of seating system forces that may be encountered in 20g frontal crash conditions.

Review of the Literature

Seating System Loads Assessed Through Computer Simulation

A computer simulation study conducted by Bertocci et al. evaluated the variation in seat loading associated with rear securement point location when using 4-point strap-type tiedowns (7). This simulation model subjected the SAEJ2249 surrogate wheelchair (187 lb) and a seated 50th-percentile Hybrid III anthropomorphic test device (ATD) to a 20g/30mph frontal sled impact in accordance with SAE J2249 pulse corridor specifications (9). In this analysis, resultant seat loads varied from 2,885 lb with rear securement points below the wheelchair center of gravity, to 4,354 lb with the rear securement points located above the wheelchair center of gravity (CG). This difference is due to the rotation of the wheelchair induced by eccentrically applied rear tiedown loads. When rear

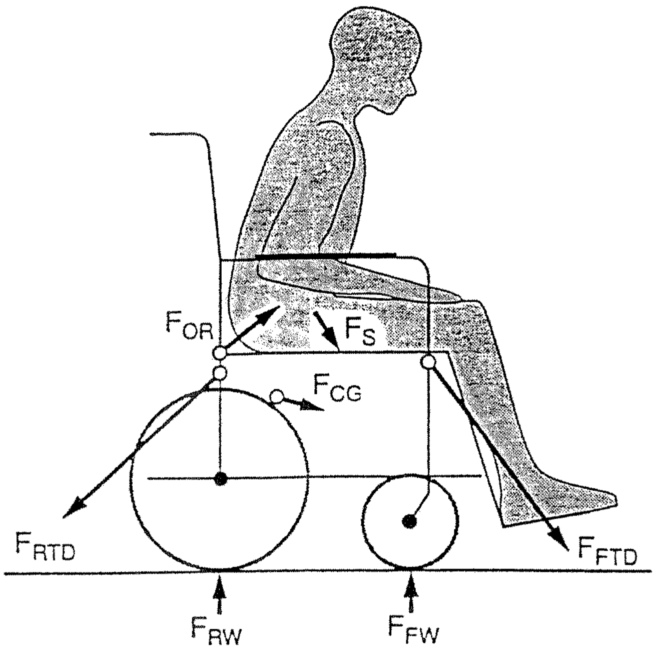

Figure 1.
Wheelchair Crash Loading Associated with Frontal Impact.
Fs=seat force, Fcg=wheelchair CG force, For=occupant restraint force, Frw & Ffw=rear and front wheel forces, Frtd & Fftd=rear and front tiedown forces

tiedowns were secured level with the wheelchair CG, a peak seat load of 3,791 lb was measured.

Seating System Loads Measured in Sled Testing

Because of the special instrumentation needs and seating modification requirements necessary to accommodate load cells to measure seating loads, only minimal seat loading experimental data exists. Two series of sled tests that estimated seat loading are described.

In tests conducted by Gu et al., pancake load cells were adapted to the wheelchair seating system through the addition of a rigid plate seat subsurface (10). Clearly this arrangement would influence the seat-loading patterns, differing from those typically seen in a more compliant commercial seating system. Sled tests conducted by Shaw relied upon pressure film placed on the seating surface, in combination with front wheel load cells to estimate vertical seat loading. Front wheel loads were summed to approximate the peak seat loads and then compared to measures from the pressure-sensitive film. This method of approximating seat loads may be conservative because the rear wheels will likely carry a portion of the seat loading, and front wheel load cells will assess only the vertical force component. The extent to which front wheel loading differs from seat loading will also depend upon the stiffness of the wheelchair frame.

Seatloads were measured during frontal impact sled testing conducted by Gu and Roy at Middlesex University Road Safety Engineering Laboratory using the ISO surrogate wheelchair (187 lb) and Hybrid II 50th-percentile male ATD (165 lb) (10). Loads were measured using pancake load cells mounted at each corner of the aluminum seat pan. With a sled pulse of 21g/30mph, the measured seat loads were near 3,340 lb. Seat loads were also estimated by Shaw in frontal impact sled tests of commercial wheelchairs with various seat types, including sling seats and contoured foam seats mounted on thin laminated wood substructures (8). In these tests a Hybrid III 50th-percentile male test dummy (165 lb) and 20g/30mph sled pulse were used. Vertical seat loads ranged from 1,900 lb to 3,200 lb, with the higher loads being associated with the more rigid surfaces (i.e., contour foam mounted on wood substructure). In each of three tests conducted by Shaw, the wooden support surfaces fractured under downward occupant loading.

METHODS

To develop crashworthy wheelchair seating system design criteria, a previously developed and validated computer simulation of a wheelchair-seated 50th-percentile male Hybrid III ATD exposed to a 20g/30mph frontal crash was used (**Figure 2**; reference 11). Rigid body modeling software, Dynaman, was used to generate the 18-segment, 17-joint occupant, along with the commercially available wheelchair. Physical dimensions and inertial characteristics of the powerbase wheelchair were replicated in the model. The Hybrid III ATD was restrained by an integrated lap and vehicle-mounted shoulder belt. An SAE J2249-compliant 20g/30mph sled impact pulse taken from actual sled testing was used to simulate a frontal crash (9). The test conditions simulated are as shown in **Table 1**.

Because wheelchair seating system designs range from softer sling type surfaces to relatively stiff planar foam support surfaces, it is of value to explore how these design variations may influence crash loading conditions. One characteristic that will differ for the wide range of seating system designs available commercially is surface stiffness. In a separate experimental study we evaluated the stiffness of commercial seat and back support surfaces through incremental static loading (12,13). Seat-

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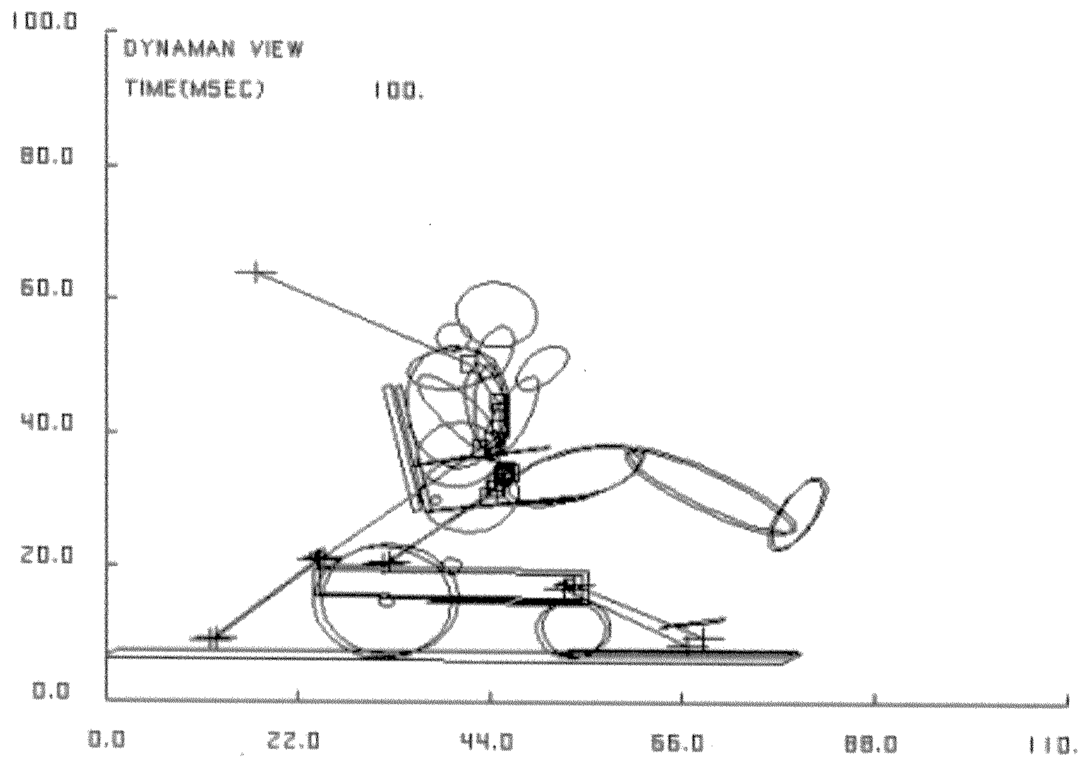

Figure 2.
Powerbase Wheelchair and 50th-Percentile Hybrid III Male Occupant Anthropomorphic Test Device Crash Simulation Model

Table 1.
Sled Impact Test and Wheelchair/Occupant Model Conditions

Wheelchair Type	Commercial Powerbase
Wheelchair Securement	4 Point Strap-type Tiedowns
Occupant Restraint	3 Point Lap and Shoulder; WC Integrated Lap
Anthropomorphic Test Dummy	50th percentile male, 168 lb, Hybrid III
Target Sled ΔEV	30 mph
Target Sled Deceleration	20 g
Wheelchair	
Wheelchair Weight	255 lb.
Wheelchair CGvertical	11″ Above Ground
Wheelchair CGhorizontal	6.5″ Forward of Rear Axle
Wheelchair Seat Angle wrt Horizontal	8°
Wheelchair Seat-Back Recline Angle wrt Vertical	12°
Wheelchair Tiedown/Securement	
Rear Securement wrt Wheelchair CGvertical	0″
Rear Tiedown Angle wrt Horizontal	40°
Front Tiedown Angle wrt Horizontal	46°
Occupant Restraint	
Shoulder Belt Anchor Height	48.5″
Shoulder Belt Anchor Outboard Location from Wheelchiar Centerline	12″
Shoulder Belt Anchor Location Aft of Wheelchair Seat Back	12.5″
Frontal Plane Shoulder Belt Angle	50° wrt Horizontal Sternum Reference
Sagittal Plane Shoulder Belt Angle Behind ATD Shoulder	25° wrt Horizontal
Sagittal Plane Lap Belt Angle	38° wrt Horizontal

back stiffness ranged from 103 lb/in to 1,650 lb/in, while seat support surfaces ranged from near 100 lb/in to 1,160 lb/in. The baseline (i.e., 100 percent) seat support surface stiffness determined experimentally and used in this model was 500 lb/in at the midrange and the seat-back support surface stiffness was 1,650 lb/in at the midrange.

A series of simulations were performed in which the seat and seat-back support surface stiffnesses were incrementally varied while all other factors were held constant. To conduct parametric analyses, seat-back stiffness was held constant at its baseline (100 percent) value while seat stiffness was varied from 25 percent to 200 percent, in 25-percent increments. Twenty-five-percent stiffness represented a softer surface than the baseline stiffness, and 200 percent represented a stiffer surface. The force-deformation seat support surface stiffness curves are shown in **Figures 3** and **4**. Next, seat stiffness was held constant while seat-back support surface stiffness was varied through the same range. Seating system loads were evaluated for all scenarios.

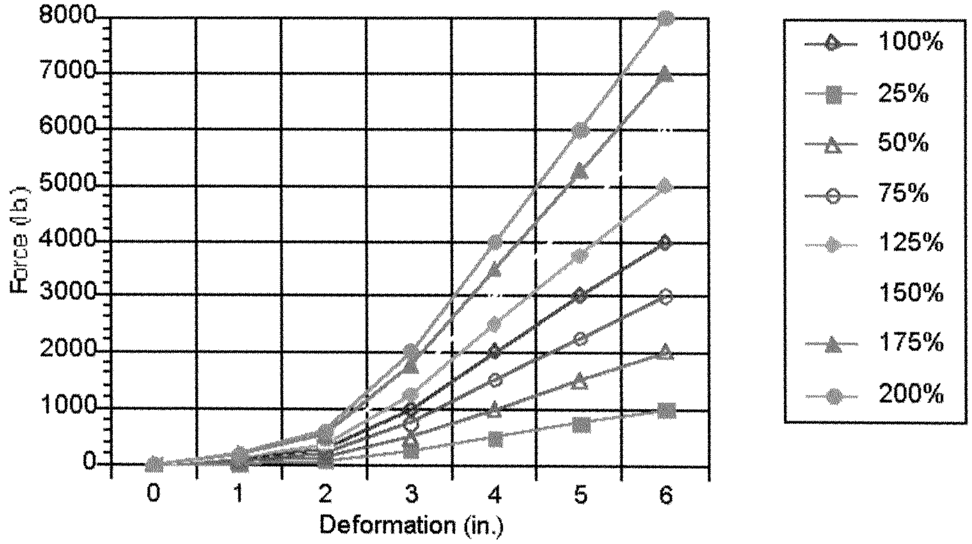

Figure 3.
Load-Deformation Stiffness Characteristics of Seat Support Surfaces

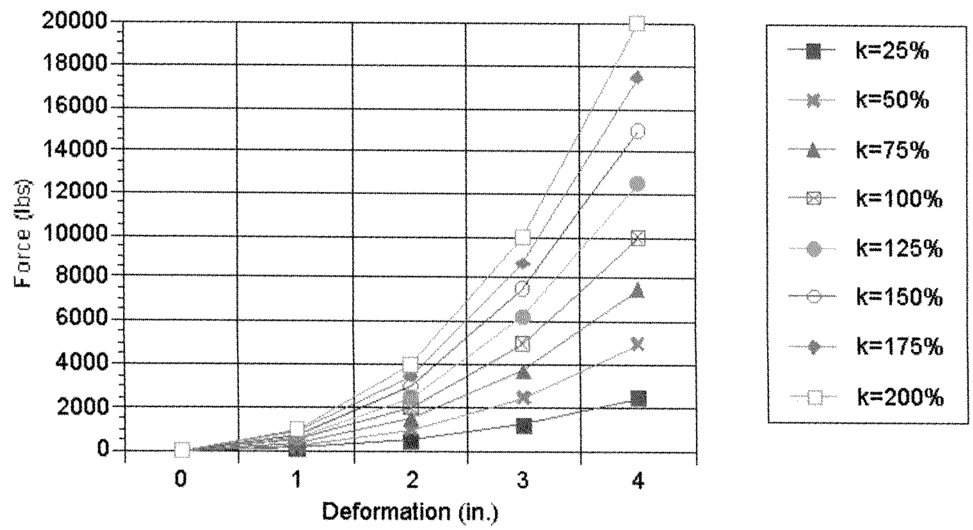

Figure 4.
Load-Deformation Stiffness Characteristics of Seat-back Support Surfaces.

A second series of simulations was conducted to explore the effects of seat-back angle on seating system loads. Seat angle was maintained at 8°, while seat-back angle was varied from 0° to 30°, in 10-degree increments.

RESULTS

Peak seat surface loading was found to vary from 819 lb for 25-percent stiffness to 3,273 lb for the 200-percent seat stiffness scenario (**Table 2**). Loading was highly dependent upon surface stiffness characteristics, increasing with increased stiffness. Load time histories showed that peak seat loading consistently occurred between 55–65 msec into the crash event (**Figure 5**). Peak seat-back loads were found to range from 1,821 lb to 2,525 lb (**Table 3**) when seat surface stiffness was held constant and seat-back stiffness was varied. Although seat-back loads varied with back surface stiffness, a direct relationship between seat-back stiffness and seat-back loading was not determined. Peak seat-back loads in a frontal crash typically occurred during the rebound phase, or between 120–130 msec into the crash event (**Figure 6**).

Table 2.
Seat Stiffness vs. Peak Seat Loads

Seat Stiffness	Peak Seat loads (lb)
25%	819
50%	1148
75%	1784
100%	2176
125%	2584
150%	2827
175%	3125
200%	3273

Table 3.
Seat Back Stiffness vs. Peak Seat-Back Loads

Back Stiffness	Peak Seat-Back loads (lb)
25%	2170
50%	2530
75%	2525
100%	2302
125%	2099
150%	1821
175%	1902
200%	2050

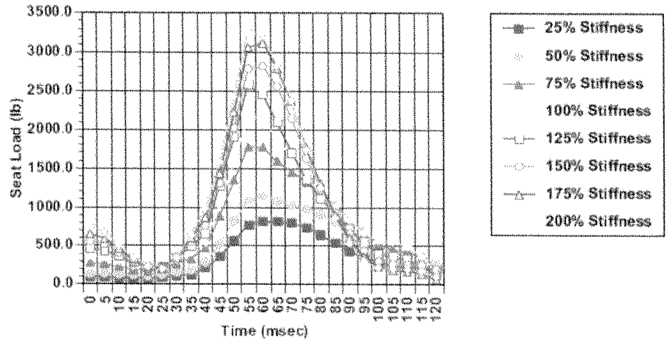

Figure 5.
Seat Load Time History for Varying Seat Surface Stiffness

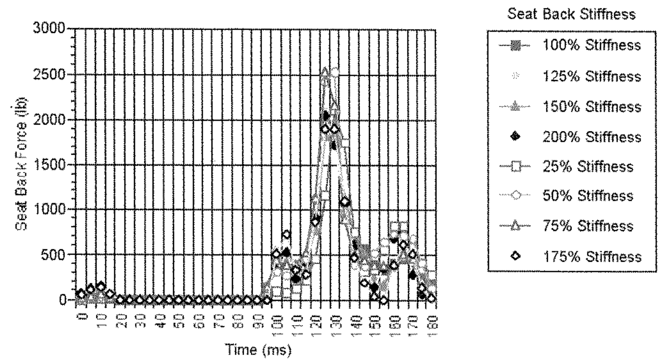

Figure 6.
Seat-back Load Time History for Varying Seat-back Surface Stiffness

Seat-back recline angle was also found to have an effect on seat and back loading. When seat and back stiffness was held constant (100 percent), seat-back loading decreased as the seat-back recline angle increased from vertical. Peak seat-back loads ranged from 2,691 lb for 0° of seat-back recline to 1,427 lb for a 30° recline angle. Peak seat loads ranged from 3,094 lb for 0° back recline to 2,148 lb associated with the 20° back recline angle (**Table 4**). Time histories for seat and back loading are shown in **Figures 7** and **8**.

Table 4.
Seat Back Angle vs. Seat and Back Loads

Seat Back Angle (deg)	Peak Seat Load (lb)	Peak Seat-Back Load (lb)
0	3094	2691
10	2256	2443
20	2148	2302
30	2519	1427

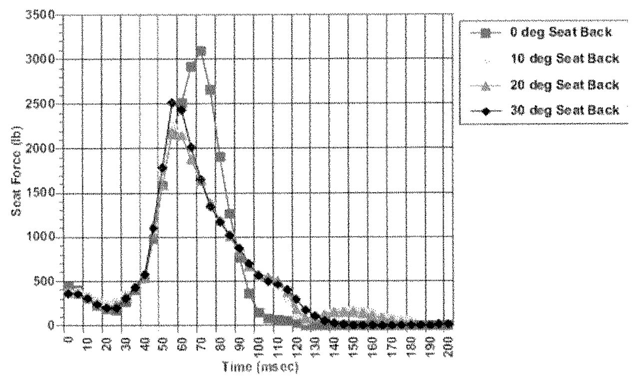

Figure 7.
Seat Load Time History for Varying Seat-back Recline Angle

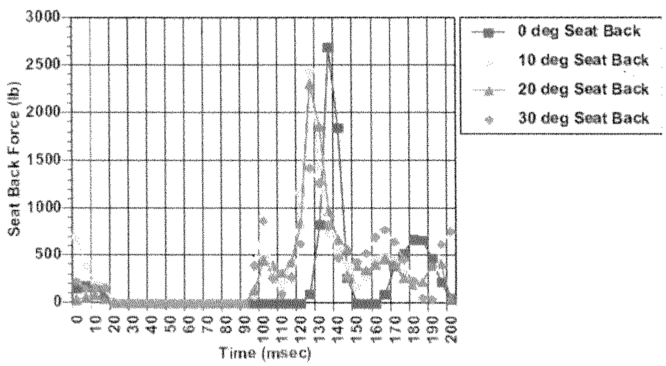

Figure 8.
Seat-back Load Time History for Varying Seat-back Recline Angle

DISCUSSION

Seat-back angle was found to influence both seat and seat-back loading conditions. Seating system loading is directly related to occupant crash kinematics. The horizontal seating surface is loaded during a frontal crash by the downward motion of the lower torso and upper legs. Increasing the seat-back recline angle tends to decrease the horizontal seat surface loading since the ATD buttocks tend to slide along the seat surface, reducing the downward loading. Similarly, increases in the seat-back recline angle tend to decrease seat-back loading due to the upper torso sliding along the seat back.

In general, increases in seat stiffness led to increased horizontal seat surface loads. Across the seat stiffness ranges evaluated, seat loading was found to increase nearly fourfold when comparing 25-percent to 200-percent stiffness scenarios. Clearly seat surface stiffness influences crash loading. However, it is important to note that softer seat surfaces encounter reduced loading since they yield to occupant loading. Such yielding permits increased pelvic/lower torso downward excursion, which under certain pelvic restraint conditions may lead to increased risk of abdominal injury or submarining (14). Therefore, it is important to recognize not only the influence of seating design on seat loading conditions, but also their effects on occupant crash kinematics.

Although a direct comparison is not possible, seat surface loading predicted through computer simulation (approximately 3,300 lb) appears to be similar to loading levels measured in limited sled tests (approximately 3,300 lb). Peak loads measured in sled tests, which approximate simulation-derived maximum seat loading, were also associated with stiffer seat surfaces. In some cases sled test seat surfaces were modified, making them more rigid, to accommodate seat load cells. Rear tiedown securement point location differences could also lead to differences in experimental *versus* simulated seating loads. Rear securement points located above the combined wheelchair and occupant CG would tend to increase seat loads due to the rearward rotation of the wheelchair in a frontal impact (7).

Unfortunately it is not possible to compare simulation-predicted seat-back loads to experimental values since to the authors' knowledge seat-back loads have not been measured in sled testing. Rebound-associated seat-back loading predicted through simulations should therefore be utilized only to identify trends occurring in response to variations in seating system characteristics. Seat-back stiffness and yielding are characteristics that have been studied in depth in the automotive industry. Seat-back response under crash loading conditions has been shown to directly influence occupant injury risk in rebound and rear impact (15–18).

Wainwright found that non-elastic permanently deformed motor vehicle seat backs reduced occupant loading and optimized occupant protection during rebound (17). Warner also found that yielding motor vehicle seats lowered the risk of injury as compared to rigid non-yielding seat backs (16). Warner further indicates that yielding seat backs better accommodate the out-of-position occupant in a crash. Strother and James found that rigid seat backs resulted in increased incidence of whiplash injuries (18). A 1997 NHTSA study based upon National Accident Sampling System (NASS) data also indicates that in rear impacts whiplash injuries occurred more frequently when seat backs maintained an upright position without permanent deformation (15). Digges and Morris conclude in their 1992 investigation of seat perform-ance in crashes that, "legitimate concerns exist over the potential increase in neck injuries and rebound injuries which might accompany strengthening seats" (19). In summary, these studies highlight the critical role that seat-back characteristics play in occupant protection.

Identification of seating system loading during a crash is also necessary to define test methods to assess crashworthiness. Currently the test methods defined by ANSI WC-19 (Wheelchairs Used as Seats in Motor Vehicles) are designed to evaluate the complete wheelchair system, which includes the seating system (19). Test methods to assess seating systems independently of their wheelchair frame would be useful for seating system manufacturers producing a variety of seating systems that may be compatible with a wide range of wheelchair frames. This study provides a first step towards defining loading conditions for such a test protocol.

CONCLUSIONS

This study has provided preliminary guidelines and trends useful in the development of crashworthy wheelchair seating systems. The use of appropriate design criteria in the development of wheelchair seating systems is crucial to occupant crash protection. Failure of any seating component in a crash will lead to increased injury risk. Seating surface stiffness and seat-back angle were found to influence seating loads under frontal crash conditions. Seat-back peak loads generated by a 20g/30mph frontal impact with a 50th-percentile male occupant were near 2,700 lb. The same impact conditions yielded peak seat loading for evaluated scenarios of approximately 3,300 lb. The findings of this study can also be used to define standards' test methods for previewing product crashworthiness. Occupants weighing more than 168 lb and crash severity greater than 20g/30mph will lead to seating system loading that is likely to be higher than reported in this study. Varying impact direction, i.e., rear or side impact, would also lead to design criteria that may be different from those reported. Future studies to address the influence of seating characteristics on occupant injury risk associated with varying impact conditions are planned.

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