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The effects of wheelchair-seating stiffness and energy absorption on occupant frontal impact kinematics and submarining risk using computer simulation

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Abstract—Many wheelchair users must travel in motor vehicles while seated in their wheelchairs. The safety features of seat assemblies are key to motor vehicle occupant crash protection. Seating system properties such as strength, stiffness, and energy absorbance have been shown to have significant influence on risk of submarining. This study investigated the effects of wheelchair seat stiffness and energy absorption properties on occupant risk of submarining during a frontal motor vehicle 20 g/30 mph impact using a validated computer crash simulation model. The results indicate that wheelchair-seating stiffness and energy absorption characteristics influence occupant kinematics associated with the risk of submarining. Softer seat surfaces and relatively high energy absorption/permanent deformation were found to produce pelvis excursion trajectories associated with increased submarining risk. Findings also suggest that the current American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America (ANSI/RESNA) WC-19 seating integrity may not adequately assess submarining risk.

Key words: crash simulation, submarining, wheelchair biomechanics, wheelchair injury, wheelchair safety, wheelchair transportation.

INTRODUCTION

The motor vehicle industry expends substantial effort on research to define optimal seat design, incorporating features that protect occupants in a crash. Since many people with disabilities often travel seated in their wheelchairs, they are unable to realize the benefits of motor vehicle seat and original equipment manufacturer (OEM) occupant restraint safety features. Unfortunately, many wheelchairs have not been designed to serve as vehicle seats and may not be crashworthy, placing wheelchair-seated travelers at increased risk of injury. Only recently with the adoption of the American National Standards Institute/Rehabilitation Engineering and Assistive Technology Society of North America (ANSI/RESNA) WC-19 standard have manufacturers been given guidance for design and testing of wheelchairs used for transport [1].

Abbreviations: ANSI = American National Standards Institute, ATD = anthropomorphic test device, H-pt = Hip-point, OEM = original equipment manufacturer, RESNA = Rehabilitation Engineering and Assistive Technology Society of North America.

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WC-19 is a voluntary industry standard that requires transit wheelchairs to be frontal impact tested to 20 g/30 mph. Frontal impact testing must be conducted with an appropriately sized test dummy suitable for the intended occupant usage of the wheelchair. Additionally, transit wheelchairs must be equipped with four securement points to interface with strap-type tie-downs and must be impact tested with a wheelchair-mounted pelvic belt. Other performance tests required by WC-19 evaluate vehicle-mounted occupant restraint accommodation, securement point accessibility, tie-down clear paths, lateral wheelchair stability, and wheelchair turning radius. The standard also requires that specialized labeling and user instructions be provided. To date, a number of wheelchair manufacturers offer transit wheelchairs that meet the WC-19 standard.

Occupant lap belt fit and anchorage location, seat design characteristics, and seated posture can all affect submarining risk [2–6]. Submarining is characterized by the pelvic restraint slipping upward over the iliac crests and loading the soft abdominal tissues. Submarining can potentially lead to severe internal injuries of organs in the abdominal region [6]. Previous motor vehicle research has shown that motion sequence of the pelvis and upper torso during a crash can be correlated with the risk of submarining [2,3]. Accordingly, kinematic analysis techniques have been used to compare and optimize automotive seating system designs. Submarining risk can be assessed through the evaluation of the forward and vertical crash motion sequence of the pelvis. In particular, the vertical downward excursion of the pelvis during a crash, which permits the lap belt to slip upward onto the abdomen, has been shown to be associated with increased levels of submarining risk [2]. Viano and Arepally suggest a submarining criterion limiting the hip joint or hip-point (H-pt) vertical excursion to be not more than 1.97 in. [3,7]. Adomeit and Heger further recommend that the main requirement for avoiding submarining is to limit the vertical downward motion of H-pt [2]. They further suggest that the sternum excursion relative to the H-pt excursion and the torso angle are also key to assessing submarining risk.

The recently adopted ANSI/RESNA WC-19 *Wheelchairs Used as Motor Vehicle Seats* standard evaluates complete wheelchair systems, including their manufacturer-provided seating system, using a 20 g/30 mph frontal sled impact test [1]. For seating surface crash integrity and submarining risk to be evaluated, compliance with WC-19 requires that the pre- to posttest change in the H-pt vertical position from an upright seated posture must not exceed 20 percent. The intent of this test criterion is to ensure that the seat surface or seat attachment hardware has not failed as a result of the test. However, it is important to note that submarining may occur without seat failure and such a scenario may escape detection by the WC-19 test criterion.

To date, little or nothing has been done to evaluate the effect of wheelchair-seating design factors on submarining risk when wheelchairs are used as motor vehicle seats. In our study, we used computer simulation techniques to investigate the effects of seat stiffness and energy absorption on wheelchair-occupant submarining risk in a frontal impact. Following recommendations of previous research in the automotive industry, we chose the H-pt excursion to quantify submarining risk. We also evaluated the test criterion established by ANSI/RESNA WC-19 to determine its effectiveness in screening for the presence of submarining risk.

METHODS

Using a previously developed and validated computer crash simulation model of a commercial wheelchair, we conducted a parametric sensitivity analysis to investigate the effect of seat stiffness and energy absorption properties on lower torso (pelvis or H-pt) excursion in a frontal crash [8]. The validated model consisted of a power base wheelchair, secured with 4-point belt-type tie-downs and a 50th percentile male Hybrid III anthropomorphic test device (sitting height of 35.7 in. and a mass of 168 lb) and restrained with a 3-point occupant restraint system. The shoulder belt was mounted to the vehicle, and the lap belt was anchored to the wheelchair. The wheelchair and occupant system was subjected to an ANSI/RESNA WC-19-compliant 20 g/30 mph frontal sled impact pulse (**Figure 1**) [1].

We conducted a parametric sensitivity analysis to investigate the influence of seating surface stiffness, varying the original seat stiffness from 25 to 200 percent in increments of 25 percent, while maintaining all other conditions constant (**Figure 2**). (Both *R*- and *G*-factors were held constant at 0.1.) For each stiffness scenario, occupant pelvis excursion, characterized by the H-pt, was recorded. The original seating system used in the model was a rigid phenolic seat pan and foam cushion, having a 667 lb/in. midrange stiffness (denoted as 100 percent in **Figure 2**). Force-deformation curves used to depict seat surface stiffness are shown in **Figure 2** and were derived under static loading conditions. These stiffness ranges were found to correlate with support surfaces of commercial wheelchair

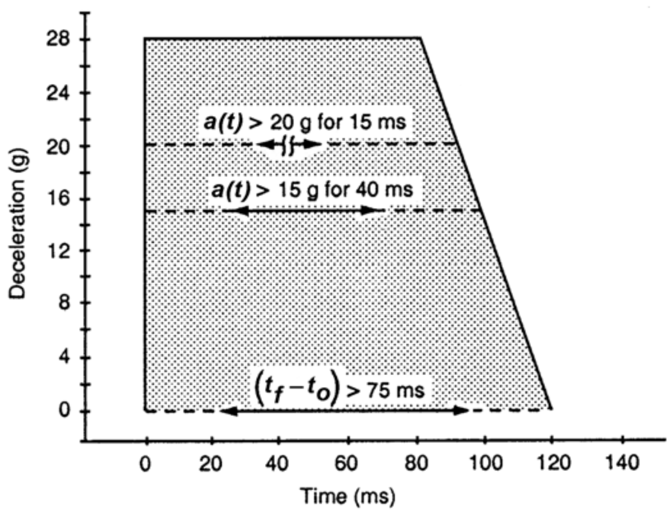

Figure 1.
ANSI/RESNA WC-19 20 g/30 mph frontal impact deceleration pulse. Note: Acceleration and deceleration of impact sled must stay within shaded area and exceed indicated levels for specified continuous (unbroken arrows) and cumulative (broken arrows) time periods.

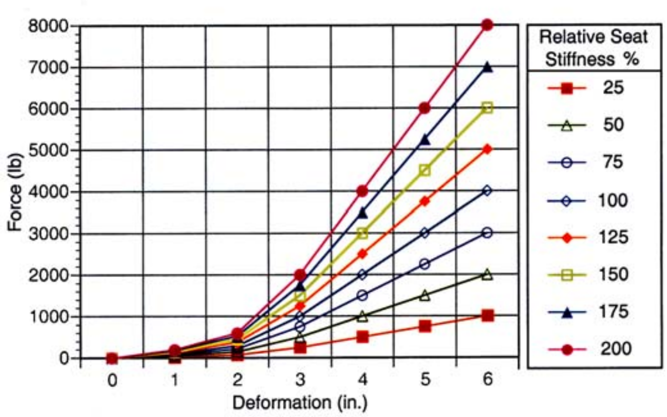

Figure 2.
Seat stiffness scenarios evaluated in parametric analysis.

seating evaluated in our laboratory under static loading conditions [9]. Across all simulations, the coefficient of friction between the seat and anthropomorphic test device (ATD) was maintained at 0.3.

Next, we examined H-pt excursion across a range of seat energy absorption properties. The two variables associated with energy absorption and permanent deformation are the *G*-factor, representing the ratio of permanent deformation to maximum deformation, and the *R*-factor, representing the ratio of energy returned during unloading to total energy associated with maximum deformation (**Figure 3**). These factors define the loading and unloading paths. A

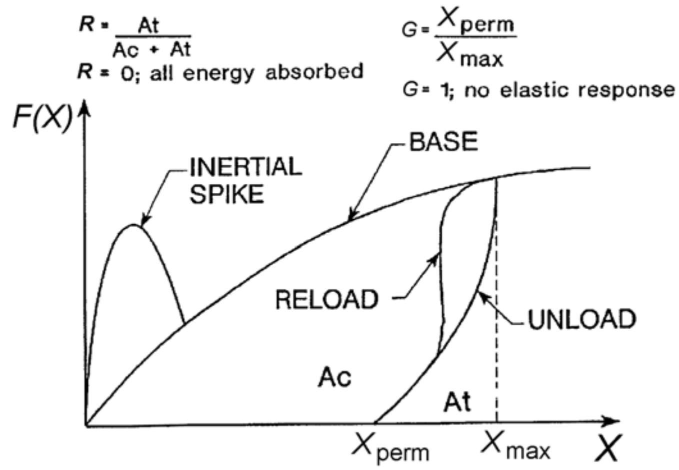

Figure 3.
Force-deformation curve: *R* (energy absorption factor) and *G* (permanent deflection factor) equations and graphical depiction of energy absorption and energy returned; permanent deformation (X_{perm}), maximum deformation (X_{max}), energy absorbed (Ac), and energy returned (At).

value of $G = 1$ represents a response with no elasticity, and a value of $R = 0$ indicates that all energy is absorbed. (Although not used in this study, the inertial spike shown in **Figure 3** accounts for inertial effects of loading and is often used to represent the response of breaking glass.) Simulations were conducted while varying the *G*- and *R*-factors according to the matrix in **Table 1**. Values of $G = 0.99$ and $R = 0.99$ were used in lieu of $G = 1.0$ and $R = 1.0$, since simulations became unstable at these values. The seating stiffness was held constant at 667 lb/in. for all simulations.

For both parametric sensitivity analyses, H-pt vertical excursion was also characterized with the use of the following methods: (1) percent difference between pre- and posttest and (2) peak H-pt vertical excursion/H-pt vertical excursion limit recommended by Viano and Arepally [3]. The first method assesses compliance with the

Table 1.
Simulation matrix of wheelchair seat *G* and *R* variable combinations used in parametric sensitivity analysis.

Conditions	$R = 0.00$	$R = 0.25$	$R = 0.50$	$R = 0.75$	$R = 0.99$
$G = 0.00$	X	X	X	X	X
$G = 0.25$	X	X	X	X	X
$G = 0.50$	X	X	X	X	X
$G = 0.75$	X	X	X	X	X
$G = 0.99$	X	X	X	X	X

ANSI/RESNA WC-19 test criterion, which limits pre- to posttest H-pt position to 20 percent.

RESULTS

Seat Stiffness Parametric Analysis Results

Figure 4 provides H-pt trajectories for midpoint (100 percent) and end point (25 and 200 percent) stiffness scenarios. As shown in **Figure 4**, the gross H-pt motion can be described as a forward vertical downward excursion followed by a rebounding rearward upward motion. Softer seat surfaces tended to have greater downward excursions followed by less upward motion associated with rebound than stiffer seat surfaces. In other words, stiffer seats rebounded the pelvis nearer to their initial starting position.

H-pt peak vertical excursions showed an increasing trend with softer (i.e., less stiff) surfaces (**Table 2**). When comparing peak downward excursions to the Viano limit of 1.97 in., we found the 25, 50, and 75 percent seat stiffness scenarios had an increased risk of submarining. However, all stiffness scenarios complied with ANSI/RESNA WC-19 criteria (percent difference pre- to posttest H-pt) (**Table 2**).

Seat Energy Absorption/Permanent Deformation Analysis Results

Figure 5 provides H-pt trajectories for $G = 0$ and $R = 0$, $G = 0.5$ and $R = 0$, and $G = 0.99$ and $R = 0$ energy absorption scenarios. Each of the scenarios begins with a forward and downward motion, but differences are observed across the scenarios on rebound. For G-values of 0 and 0.5, H-pt rebound is either rearward or slightly rearward and upward, followed by an abrupt upward motion for both scenarios. For $G = 0.99$, rebound consists of a rearward and downward motion followed by an abrupt upward motion. The greatest downward excursion of the pelvis is observed in the scenario where seat energy absorption/permanent deformation is high ($G = 0.99$).

The parametric sensitivity analysis of seat energy absorption/permanent deformation revealed that scenarios with G-factors of 0.75 and 0.99 combined with R-factors from 0.00 to 0.75 may increase occupant-submarining risk. In cases where permanent deformation is high ($G = 0.75$, $G = 0.99$ with $R = 0$ to 0.75), peak H-pt vertical downward excursions exceeded the Viano limit of 1.97 in. (**Table 3**). When pre- to posttest H-pt excursions were compared to the WC-19 criterion, all scenarios complied with the criterion.

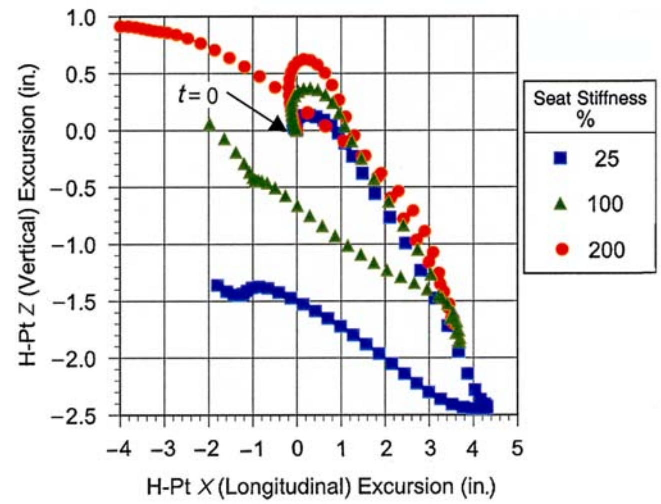

Figure 4.
Trajectory of H-pt vertical and horizontal excursion for various seat stiffness scenarios.

Table 2.
Hybrid III ATD H-pt kinematics for various seat stiffness scenarios.

Seat Surface Stiffness (%)	Peak H-pt$_{vert}$	Peak H-pt$_{hori}$	% Diff Pre- to Posttest H-pt$_{vert}$*	Peak H-pt$_{vert}$/ Viano Limit†
25 (Softer)	–2.45‡	4.32	12	1.24‡
50	–2.18‡	4.03	7	1.11‡
75	–1.99‡	3.85	2	1.00‡
100	–1.86	3.70	–1	0.94
125	–1.79	3.60	0	0.91
150	–1.66	3.53	–4	0.84
175	–1.57	3.43	–5	0.79
200 (Firmer)	–1.69	3.56	–8	0.86

*ANSI/RESNA WC-19 Test Criterion. For simulations, posttest set to 120 ms. Negative % values denote a vertically higher position at $t = 120$ ms.
†H-pt$_{vert}$ limit recommended by Viano and Arepally = 1.97 in. Values greater than 1.0 exceed limit.
‡Cells indicate increased submarining risk.

DISCUSSION

Our sensitivity analysis indicates that seat surface stiffness and seat energy absorption characteristics do influence wheelchair-seated H-pt kinematics during a frontal impact and therefore do influence risk of submarining. Seat stiffness scenarios that represent softer seats

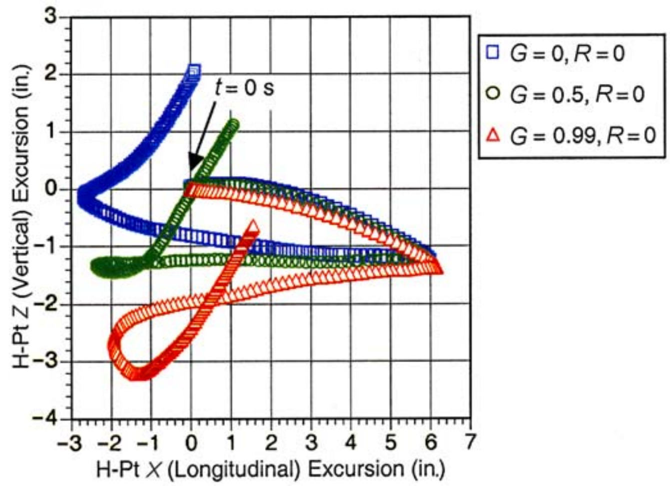

Figure 5.
Trajectory of H-pt vertical and horizontal excursion for various seat energy absorption scenarios.

appear to present the greatest risk of submarining. The levels of stiffness associated with these scenarios coincide with those found in sling-type wheelchair-seating systems [10].

Our results indicate that seat energy absorption is also a factor that influences submarining risk in wheelchair-seated occupants exposed to frontal impact. In particular, those seating scenarios with high energy absorption/permanent deformation led to occupant kinematics, which are associated with submarining risk.

Our analysis also shows that the ANSI/RESNA WC-19 test criterion for submarining and seat integrity may fail to identify submarining risk that may be present without seat failure. Although the WC-19 submarining criterion (20 percent difference in pre- to posttest vertical hip excursion) was not exceeded for any energy absorption scenario, the Viano and Arepally limit (1.97 in. downward) was exceeded in several simulation scenarios. Similarly, all seat stiffness scenarios met WC-19 criteria despite softer seat scenarios failing to meet the Viano and Arepally recommended H-pt excursion criteria. While WC-19 was a first attempt to capture seat failure, a more stringent criterion that tracks H-pt excursion throughout the entire impact may be more effective at elucidating submarining risk.

While this study evaluates submarining risk using H-pt kinematics, it is important to note that lap belt loading is also a critical factor in predicting submarining risk. Leung et al. predicted that injurious submarining occurs only when the lap belt force is 680 lb or more and the belt has slipped over the iliac crests [6]. Leung indicated that the belt slipping onto the abdomen is unlikely to lead to submarining injury if belt loading is low. An experimental means to simultaneously capture both belt loading and pelvic belt kinematics was developed by Rouhana et al. through the "frangible abdomen" [11]. The frangible abdomen is a crushable Styrofoam abdominal insert designed to be compatible with the Hybrid III dummy. This biofidelic abdominal insert has been developed so that it assesses the incidence of submarining, as well as the severity or risk of injury through measurement of insert crush depth. As a next step, our computer simulation study predicting that the risk of submarining could be enhanced with the use of validating sled tests employing a Hybrid III dummy that incorporates a frangible abdomen insert. Further enhancements to our study could also be achieved through the assessment of lap belt force during periods of peak downward excursion of the pelvis.

Table 3.
H-pt kinematics for seat energy absorption scenarios compared to Viano limit [3] and ANSI/RESNA WC-19 standard criterion for *R*-factors 0.00, 0.25, 0.50, 0.75, and 1.00.

Seat Surface *G*-Factor	*R*-Factor = 0.00			*R*-Factor = 0.25			*R*-Factor = 0.50			*R*-factor = 0.75			*R*-factor = 1.00		
	Peak $H\text{-}pt_{vert}$	Peak $H\text{-}pt_{vert}$/ Viano Limit	WC19 % Diff Pre- to Post- $H\text{-}pt_{vert}$	Peak $H\text{-}pt_{vert}$	Peak $H\text{-}pt_{vert}$/ Viano Limit	WC19 % Diff Pre- to Post- $H\text{-}pt_{vert}$	Peak $H\text{-}pt_{vert}$	Peak $H\text{-}pt_{vert}$/ Viano Limit	WC19 % Diff Pre- to Post- $H\text{-}pt_{vert}$	Peak $H\text{-}pt_{vert}$	Peak $H\text{-}pt_{vert}$/ Viano Limit	WC19 % Diff Pre- to Post $H\text{-}pt_{vert}$	Peak $H\text{-}pt_{vert}$	Peak $H\text{-}pt_{vert}$/ Viano Limit	WC19 % Diff Pre- to Post- $H\text{-}pt_{vert}$
0.00	−1.28	0.65	−9.15	−1.28	0.65	−9.15	−1.28	0.65	−9.15	−1.29	0.66	−8.97	−1.28	0.65	−8.58
0.25	−1.30	0.66	−6.46	−1.30	0.66	−6.46	−1.30	0.66	−6.46	−1.27	0.64	−8.13	−1.28	0.65	−8.58
0.50	−1.45	0.74	−4.94	−1.45	0.74	−4.94	−1.56	0.79	−3.95	−1.28	0.65	−5.79	−1.28	0.65	−8.58
0.75	−2.5*	1.27*	−1.50	−2.45*	1.24*	−0.36	−2.43*	1.23*	0.06	−2.43*	1.23*	0.06	−1.28	0.65	−8.58
0.99	−3.2*	1.63*	2.89	−3.2*	1.63*	4.12	−3.2*	1.63*	4.12	−3.2*	1.63*	4.12	−1.28	0.65	−8.58

*Cells indicate that criterion was exceeded.
Note: Negative % indicates final H-pt position above initial position at t = 120 ms.

Since seat design has a direct effect on pelvic excursion and hence submarining risk during a crash, our study supports the need for wheelchair-seating system manufacturers to begin evaluating "anti-submarining" strategies such as those used in the automotive seating industry. A study by Adomeit and Heger suggests that a seat design approach incorporating a sheet metal pan with a reinforced front wall and energy-absorbing foam at the front of the seat can effectively reduce submarining risk [2]. Frontal impact sled tests conducted by Bacon suggests increased seat friction and a slight upward seat angle tended to reduce submarining risk [5]. While the exact structure of a motor vehicle seat may not be able to be replicated in a wheelchair seat, characteristics of successful motor vehicle seat design should attempt to be incorporated into wheelchair seating. For example, anti-submarining seat pan designs could be easily incorporated into drop seats used to support wheelchair seat cushions. Cushions could also attempt to incorporate composite multifoam designs that reduce submarining risk while maintaining pressure-relieving and comfort characteristics.

CONCLUSIONS

This study demonstrated the usefulness of computer simulation techniques by systematically assessing the effects of wheelchair-seating design on occupant injury risk. Our findings indicate that seat surface stiffness and energy absorption influence submarining risk in a wheelchair-seated occupant exposed to a frontal crash. As seating stiffness is decreased, an increase in submarining risk was found. Also, as energy absorption was increased, an increase in submarining was present. Our study also showed that the existing ANSI/RESNA WC-19 seat integrity criteria may not be sensitive enough to detect the presence of submarining.

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