

Rear-impact neck protection devices for adult wheelchair users

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Abstract—Many wheelchair users remain in their wheelchairs during transit. Safety research for wheelchair users has focused mainly on frontal impact. However, although they are generally less severe, rear-impact injuries are expensive and difficult to treat and whiplash injury protection for adult wheelchair users remains poorly understood. In this article, 10 g (16 km/h) rear-impact sled tests conducted with the Biofidelic Rear Impact Dummy II or BioRID-II (Denton ATD Inc and Chalmers University of Technology; Gothenburg, Sweden) seated in a rigid wheelchair with no head restraint showed that Abbreviated Injury Scale-score 1 neck injury risk evaluated with the neck injury criterion (NIC) and Nkm criterion is substantially above proposed threshold levels. A prototype wheelchair head restraint was developed and tested together with an existing commercial head restraint (Rolko; Borgholzhausen, Germany) in the same 10 g (16 km/h) rear impact. Both head restraints reduced the injury scores substantially. NIC test scores for the head restraints with no gap ranged from 18 to 24 (approximately 20%–30% chance of neck injury symptoms of duration >1 month) compared with test scores for no head restraints that ranged from 34 to 37 (approximately 95% chance of neck injury). The corresponding extension-posterior Nkm scores with no gap ranged from 0.30 to 0.35 (approximately 5% chance of neck injury) compared with no head restraint of 1.16 (approximately 45% chance of neck injury symptoms). However, the number of sled tests performed was small (three with no head restraint and six with a head restraint), and these results should be considered mainly trends. Preliminary results also showed that the horizontal gap between the head and the wheelchair head-restraint cushion should be as small possible.

Key words: crash test dummy, head restraint, neck injury criteria, occupant protection, rear impact, rehabilitation, restraint, sled test, wheelchair, whiplash.

INTRODUCTION

We estimate that a minimum of 700 wheelchair users in Ireland take at least 500,000 road trips annually, remaining in their wheelchairs during transit. In the United States, about 1.6 million people residing outside institutions use wheelchairs [1], and wheelchair user transportation safety is therefore a key consideration. Frontal collisions dominate serious vehicle collisions [2], and to date, the main focus of wheelchair safety research has been preventing injury through occupant retention in frontal impacts [3–5] and developing crash protection for pediatric cases [6]. Main developments have been in wheelchair tie-down and occupant restraint systems (WTORSs), which are stipulated in a series of frontal impact safety standards in International Organization for Standardization (ISO) 10542 [7]. Wheelchairs are now commonly tested for crash integrity according to ISO

Abbreviations: AIS1 = Abbreviated Injury Scale-score 1, BioRID-II = Biofidelic Rear Impact Dummy II, COG = center of gravity, FMVSS = Federal Motor Vehicle Safety Standard, HIC = head injury criterion, IIWPG = Insurance Institute for Whiplash Prevention Group, ISO = International Organization for Standardization, NDC = neck displacement criterion, NIC = neck injury criterion, T = thoracic, WTORS = wheelchair tie-down and occupant restraint system.

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7176:19. However, although rear impact accounts for only 5 percent of fatalities [8], this crash mode results in 30 percent of automotive-related trauma in the general population, and low-severity rear impact accounts for more long-term injury than any other crash mode [8]. In a low-velocity rear impact, the seat back accelerates the torso relative to the head [9], frequently causing a neck injury called “whiplash” [10], which is expensive to treat and can have significant long-term consequences [11].

The kinematics of whiplash in conventional vehicle seats is well documented (**Figure 1(a)–(b)**): the thorax is pushed forward by the seat back [12], and the upper and lower portions of the neck are forced into flexion and hyperextension, respectively, resulting in the well-known S-shaped configuration for the cervical vertebrae [9] (**Figure 1(b)**). The shear force at the skull base results in a moment about the head’s center of gravity (COG), and the consequent head rotation hyperextends the entire neck (**Figure 1(c)**), followed by the head rebounding forward (**Figure 1(d)**), known as flexion [9].

No consensus exists in research regarding injury mechanisms or even which anatomical structures are involved in long-term Abbreviated Injury Scale-score 1 (AIS1) whiplash injury [13–15], but research agrees that differential motion of the head and thorax during impact causes the injuries observed clinically [9,16]. These injuries can be limited by a high seat back or a separate head restraint positioned behind and close to the occupant’s head [16] (**Figure 1(e)**). Accordingly, Federal Motor Vehicle Safety Standard (FMVSS) 202 requires head restraints in passenger motor vehicle seats to limit rearward angular displacement of the head with respect to the torso during an 8 g forward acceleration pulse [17]. An alternative static test is also possible, in which the head restraint and seat back are loaded to a torque of 373 Nm and the resulting head-restraint displacement must remain <10 cm.

For wheelchair user rear-impact protection, Schneider [18] and Seeger and Caudry [19] recognized the obvious analogy with conventional motor vehicle seats more than 25 years ago and recommended a head restraint to prevent whiplash during transit. However, provision of a head restraint on wheelchairs used in transportation is still not required and the crashworthiness of postural head supports or head restraints (**Figure 2(a)**) are generally unknown, since FMVSS 202 does not apply and no other appropriate standard exists. In the 1990s, Karg and Sprigle [20] evaluated commercially available wheelchair head restraints using the static FMVSS 202 test [17]. In all cases, head-restraint failure occurred in the interface bracket with the seat back, in the seat back itself (**Figure 2(b)**), or by plastic bending in the vertical adjuster (**Figure 2(c)**), and redesign of the vertical adjuster was recommended. However, no dynamic tests were performed, and evaluation of criteria for neck injuries was therefore not possible.

Recently, Manary et al. found structural failures in all wheelchair and tie-down configurations subjected to a rear-impact pulse of 12 to 14 g [21]. Failure occurred because of breakages of wheelchair components and front WTORS due to their increased loading in rear impact. Senin et al. used a less-severe rear-impact pulse (8 g) [22], and they found no breakages of the securement system because the impact pulse was mostly absorbed by the back support, which failed because of plastic deformation of the vertical supports. Very recently, rear-impact-injury risk assessment has been conducted for pediatric wheelchair occupants [23]. These authors performed six 25 km/h (11 g) rear-impact sled tests using a 6-year-old Hybrid III dummy (Crash Test Dummy Labs; Eden, New York) seated in commercial wheelchairs with and without a slightly modified commercial head restraint. They found that the presence of the head restraint significantly reduced the predicted injury risk. However, the change in



Figure 1.

Typical whiplash sequence: (a) initial position, (b) S-shape, (c) hyperextension, and (d) flexion. (e) Conventional head restraint. *Source:* Reproduced from Munoz D, Mansilla A, Lopez-Valdes F, Martin R. A study of current neck injury criteria used for whiplash analysis—Proposal of a new criterion involving upper-and lower neck load cells. Proceedings of the 19th Experimental Safety Vehicles Conference; 2005 Jun 6–9; Washington, DC. Washington (DC): National Highway Traffic Safety Administration; 2005.

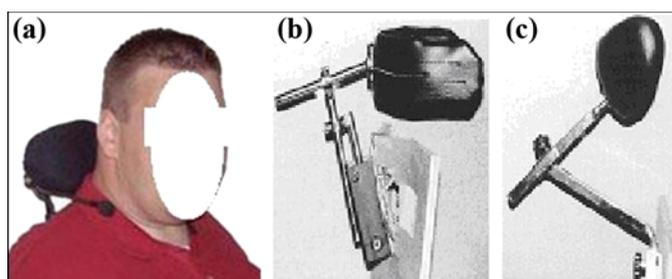


Figure 2.

(a) Wheelchair postural support/head restraint (*source: <http://www.accesstr.com>*), (b) plywood seat-back-pullout failure, and (c) vertical adjustor bending moment failure. *Source: Karg P, Sprigle S. Development of test methodologies for determining the safety of wheelchair headrest systems during vehicle transport. J Rehabil Res Dev. 1996;33(3):290–304. PMID: 88236761*

velocity (D_v) of the crash pulse was quite high and the injury criteria evaluated were the skull fracture head injury criterion (HIC), the Nij direct impact neck injury predictor, and concussion tolerance, and these criteria are not commonly used for low-speed neck-injury assessment [13,24–25]. Consequently, whether the results from this work can be extrapolated to whiplash injuries in adult wheelchair users is unclear, and no literature directly relating to the effectiveness of adult wheelchair user head restraints for whiplash protection appears to be available since the work of Karg and Sprigle [20]. Therefore, the goals of this study were to test the injury risk of adult wheelchair occupants with no head restraint and to develop a head restraint and test its effectiveness compared with a commercially available head restraint in rear-impact sled tests. The test results could then be used to draw conclusions about the two devices and recommend future work.

METHODS

The absence of a head restraint significantly increases the risk of whiplash injuries to the neck for conventional motor vehicle seat occupants in a rear impact [16], but no published evidence demonstrates that this finding is also true for adult wheelchair occupants. To address this concern, we report three kinds of rear-impact tests. They are rear-impact sled tests of wheelchair occupants with—

1. No head restraint to predict baseline data of neck injury for adult occupants of rigid wheelchairs without a head restraint.

2. A new prototype head restraint.
3. An existing commercial head restraint.

The sled tests and development of the prototype head restraint will now be described in more detail.

Rear-Impact Testing with No Head Restraint

We performed three rear-impact wheelchair sled tests with no head restraint to predict baseline neck injury data for adult occupants of rigid wheelchairs without a head restraint who were seated in vehicles subjected to a rear-impact acceleration pulse. The 50 percentile male Biofidelic Rear Impact Dummy II (BioRID-II) (Denton ATD Inc and Chalmers University of Technology; Gothenburg, Sweden) was chosen because it has been validated for rear impact in the D_v range of 7 to 15 km/h by comparison with human volunteer and cadaver response data [26]. It has also been shown in comparison with 8 km/h volunteer tests to be more biofidelic than the Hybrid III, RID II (TNO Automotive; Delft, the Netherlands), or Thor dummies (National Highway Traffic Safety Administration; Washington, DC) [27]. A comparison between the BioRID P3 (a precursor of BioRID-II) (Chalmers University of Technology; Gothenburg, Sweden) and the Hybrid III for rear-impact D_v of 15 km/h and 25 km/h found that the BioRID-II showed higher biofidelity than the Hybrid III, even at these moderate speeds [28]. Furthermore, the Insurance Institute for Whiplash Prevention Group (IIWPG) recommends the BioRID-II for whiplash injury evaluation [29].

The dummy was seated in a rigid wheelchair similar to the Society of Automotive Engineers J2252 surrogate [30], though a lower mass of 37 kg was used because testing the WTORS was not a goal of these tests. The seat and back supports of the wheelchair were constructed of plywood with 2.5 cm-thick Plastazote™ polyethylene foam padding used on the back support. The rigid back support increases loading of the spine [31–32]. However, because the goal was to establish the influence of a head restraint, confounding effects due to wheelchair cushioning and structural deformation were avoided through the use of a rigid wheelchair. Previous researchers took a similar approach for the validation of the BioRID-II [33] and the static evaluation of wheelchair head restraints similarly [20].

The IIWPG 16 km/h 10 g rear-impact pulse was used in the tests [29] because it is reported to represent an acceleration pulse for whiplash injuries [29]. Similarly, analysis of German accident data concluded that a speed

range of 10 to 20 km/h Δv represents the main problem area for soft-tissue neck injuries [34]. An Unwin carabiner-type anchorage and webbing tie-down restraint system (SWR/10) (C.N. Unwin Ltd; Martock, Somerset, United Kingdom) and three-point occupant belt system were used (**Figure 3**). After each test, the wheelchair and WTORS were inspected for damage. Thatcham Crash Laboratory (where the tests were performed; Thatcham, United Kingdom) required a mechanical stop to prevent damage to the dummy neck by severe hyperextension (**Figure 3**). Unfortunately, this stipulation prevented evaluation of the end stages of neck hyperextension. However, the mechanical stop was sufficiently far away from the head for considerable hyperextension of the neck and had no influence until the hyperextension had already occurred.

Prototype Head Restraint

Karg and Sprigle showed that many head-restraint devices failed in rear impact because of excessive bending moments in the vertical adjuster or through pullout forces on the seat back and that a new prototype head restraint must address these problems [20]. The proposed design is shown in **Figure 4**. The components are the head-restraint cushion, cushion pivot, cushion pivot set

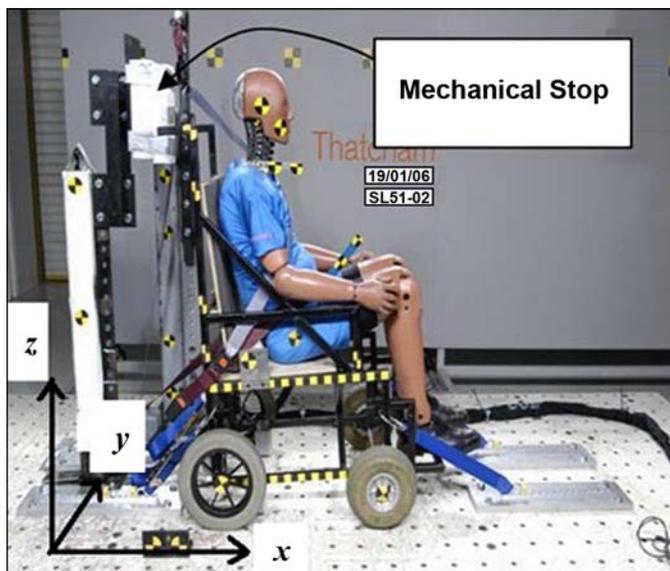


Figure 3. Test setup for no head restraint including mechanical stop to prevent excessive hyperextension of neck. Coordinate system for analysis is also shown.

screws, stalk pivot, stalk pivot set screw, upper-attachment clips, and lower-attachment clips. The device is based on the principle of reducing the bending moment in the vertical upright stalk and reducing the risk of pullout forces separating the head restraint from the seat back. It is shown attached to the surrogate wheelchair in **Figure 5**.

In a rear impact, the moment arm of the head contact force on the head restraint about the lower-head-restraint attachment clips at G is L_1 (**Figure 5(c)**). This moment arm is counteracted by tensile loading in the upper head-restraint attachment clips at F. The vertical separation of the attachment clips is L_2 and the ratio of L_1/L_2 is 3.5, compared with 4.6 as estimated from one of the commercial head restraints that failed in the evaluation by Karg

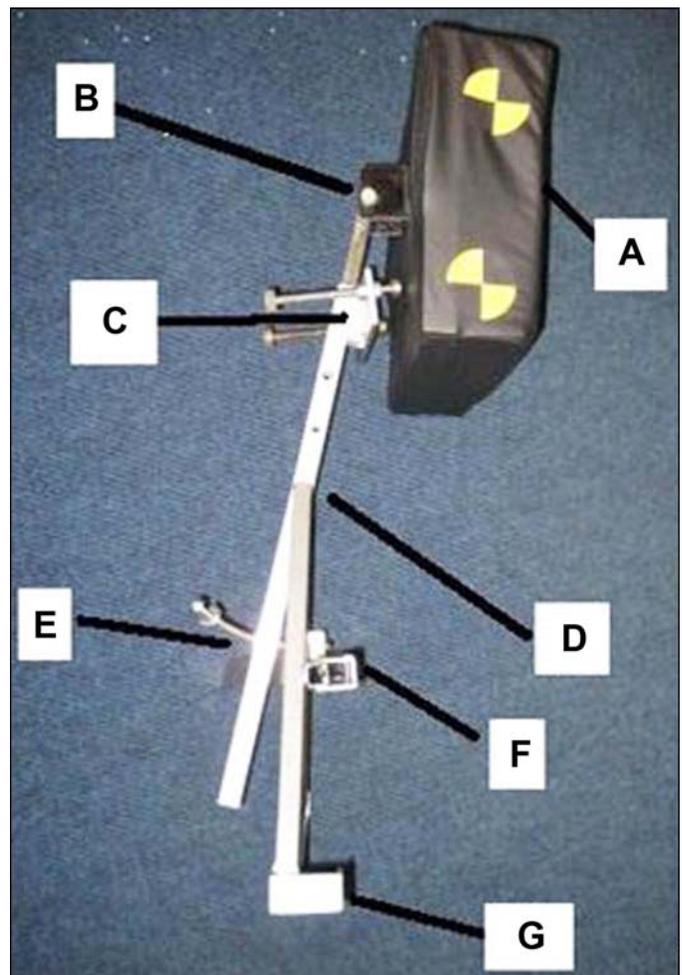


Figure 4. Proposed head-restraint design: cushion (A), cushion pivot (B), cushion pivot set screws (C), stalk pivot (D), stalk pivot set screw (E), upper-attachment clips (F), and lower-attachment clips (G).

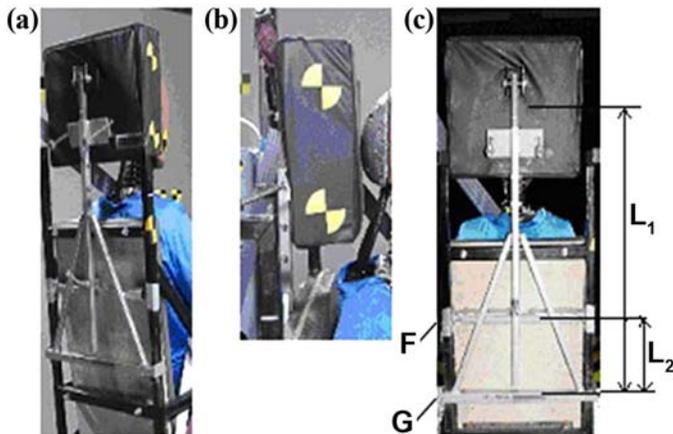


Figure 5.

Prototype head restraint attached to surrogate wheelchair: (a) isometric view from rear, (b) side view, and (c) rear view showing the upper-head-restraint attachment clips at F, lower-head-restraint attachment clips at G, moment arm of head contact force on head restraint about lower-head-restraint support at G (L_1), and vertical separation between F and G (L_2).

and Sprigle [20]. The head-restraint frame is attached to the seat back by way of steel clips around the seat-back uprights, rather than through screws into the plywood seat back. The head-restraint cushion angle can be adjusted with respect to the stalk by the pivot at B, and the stalk angle can be adjusted relative to the lower head-restraint frame by a pivot at D as shown in **Figure 4**, allowing correct placement of the cushion just behind the occupant's head. These pivot angles can be fixed with the set screws at C and E. Two prototypes were constructed from the same materials: a lighter version of 19 mm box section steel and a heavier version of 25 mm box section. The principal dimensions and the materials used in the design are given in **Appendix 1** (available online only).

Commercial Head Restraint

To assess whether wheelchair head-restraint designs have improved since the work of Karg and Sprigle [20], we chose the commercially available Rolko [35] head restraint (Borgholzhausen, Germany) (**Figure 6**) because it is commonly used by the Enable Ireland Postural Management (Seating) Service in Dublin [36], Ireland.

Rear-Impact Testing with Head Restraints

The new prototype and the Rolko head restraints were tested with the same rear-impact test procedure as previously described for no head restraint. The test matrix for all tests performed is shown in **Table 1**, show-



Figure 6.

Rolko head restraint (Borgholzhausen, Germany) on surrogate wheelchair

ing three no-head-restraint tests (no_hr_01, 02, and 03) and six head-restraint tests. Two of the head-restraint tests were performed with the heavier prototype (hr_01 and 02), two with the lighter prototype (hr_03 and 04), and two with the Rolko (hr_05 and 06). In the tests with head restraints, the head-restraint cushion was directly behind the head with no horizontal gap, except in one where the Rolko head-restraint cushion was positioned initially 50 mm behind the head (hr_06).

Table 1.

Insurance Institute for Whiplash Prevention Group Biofidelic Rear Impact Dummy II (Denton ATD Inc and Chalmers University of Technology; Gothenburg, Sweden) whiplash tests performed in this study of prototype and Rolko (Borgholzhausen, Germany) head restraints.

Code	Description of Head Restraint
no_hr_01	No head restraint
no_hr_02	No head restraint
no_hr_03	No head restraint
hr_01	Heavier prototype (no gap)
hr_02	Heavier prototype (no gap)
hr_03	Lighter prototype (no gap)
hr_04	Lighter prototype (no gap)
hr_05	Rolko (no gap)
hr_06	Rolko (50 mm gap)

hr = head restraint (code only).

Injury Criteria

AIS1 whiplash injuries occur because of indirect loading of the neck. Therefore, well-known criteria for direct impact loading such as the HIC skull fracture predictor [37] and the Nij neck injury predictor [38–39], which was proposed for assessing severe neck injuries in frontal impacts, are not appropriate injury criteria for whiplash assessment [24,40]. However, the injury mechanisms for whiplash are not fully understood [24], and therefore, the biomechanical validity of the many proposed criteria for whiplash such as the neck injury criterion (NIC) [41], the Nkm [25], and neck displacement criterion (NDC) [42] are questionable [24]. Nonetheless, Folksam, a Swedish insurance company, has fitted more than 40,000 cars with crash pulse recorders that record the vehicle if a collision occurs. By linking with injury records from hospitals and performing Madymo (TNO Automotive Safety Solutions; Delft, the Netherlands) simulations of these real-world accidents using a BioRID-II model and the crash pulse recorder data as input, Kullgren et al. [43] found a clear correlation between both the NIC [41] and the Nkm [25] criterion and the observed real-world whiplash injuries. A poorer correlation with the NDC and lower neck-bending moment was found. In consequence, we used the NIC and the Nkm in this article to assess neck injury likelihood for wheelchair users in rear impact. The NIC [41] quantifies the initial retraction phase of a low-speed rear impact and is calculated from the relative x -component acceleration (International System of Units) at the level of the first thoracic (T1) vertebra and the head COG as

$$a_{\text{rel}} = a_x^{\text{T1}} - a_x^{\text{head}},$$

$$v_{\text{rel}} = \int a_{\text{rel}} dt, \quad (1)$$

and

$$\text{NIC} = 0.2 \times a_{\text{rel}} + v_{\text{rel}}^2,$$

where a = acceleration, x = displacement, and v = velocity.

Boström et al. proposed a NIC tolerance of $15 \text{ m}^2/\text{s}^2$ [41], and experimental neck trauma tests in a group of small females and midsized males were used to conclude that this threshold is reasonable for the onset of neck injury [44]. The Nkm [25] criterion predicts the risk of

neck injury by merging the upper-neck shear force (F_x) and bending moment (M_y) according to

$$\text{Nkm} = \frac{|F_x(t)|}{F_{\text{int}}} + \frac{|M_y(t)|}{M_{\text{int}}}, \quad (2)$$

where F_{int} = the critical shear force, M_{int} = bending moment, and t = time. This criterion distinguishes between four possible modes, depending on the directions of the loads, and the critical moment is lower in extension than in flexion (**Table 2**). An Nkm score greater than 1 in any of the four cases predicts a neck injury in that mode.

However, because of the inherent variability in injury risk for different individuals, risk probabilities are more appropriate to consider than a single threshold level predicting the occurrence or nonoccurrence of injury. Therefore, to assess whiplash injury risk for adult wheelchair users (**Figure 7**) in this article, we will use the risk probabilities associated with neck injuries with symptoms lasting >1 month and the calculated NIC and Nkm scores derived by Kullgren et al. from accident reconstructions [43]. One can see that the proposed NIC threshold of $15 \text{ m}^2/\text{s}^2$ [41] is associated with approximately 20 percent risk of neck injuries, while the proposed Nkm threshold of 1 [25] is associated with approximately 30 percent risk of neck injuries with symptoms lasting >1 month.

RESULTS

We present the results for the no-head-restraint tests first, followed by the test results with head restraints. **Figure 8** shows the IIWPG rear-impact pulse, and the

Table 2.

Critical values for the Nkm criterion* using 50 percentile male dummy. *Source:* Schmitt K, Muser M, Niederer P. A new neck injury criterion candidate for rear-end collisions taking into account shear forces and bending moments. Proceedings of the 17th Experimental Safety Vehicles Conference; 2001 Jun 4–7; Amsterdam, the Netherlands. Washington (DC): National Highway Traffic Safety Administration; 2001.

Nkm	M_y	$F_x: F_{\text{int}} = 845 \text{ N}$
Flexion Anterior	>0: $M_{\text{int}} = 88.1 \text{ Nm}$	>0
Flexion Posterior	>0: $M_{\text{int}} = 88.1 \text{ Nm}$	<0
Extension Anterior	<0: $M_{\text{int}} = 47.5 \text{ Nm}$	>0
Extension Posterior	<0: $M_{\text{int}} = 47.5 \text{ Nm}$	<0

*New criterion used to determine neck injury.

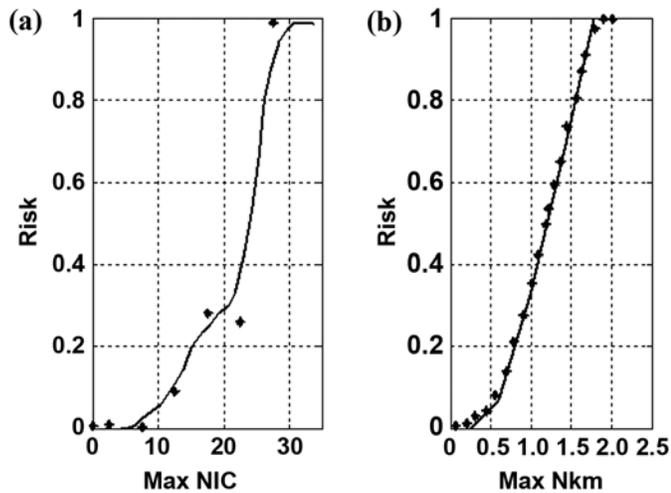


Figure 7. Relationship between neck injuries with symptoms lasting >1 month and calculated (a) neck injury criterion (NIC) and (b) Nkm scores derived from accident reconstructions. (Adapted from Kullgren A, Eriksson L, Böstrom O, Krafft M. Validation of neck injury criteria using reconstructed real-life rear-end crashes with recorded crash pulses. Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles; 2003 May 19–22; Nagoya, Japan. Washington (DC): National Highway Traffic Safety Administration; 2003.) Max = maximum.

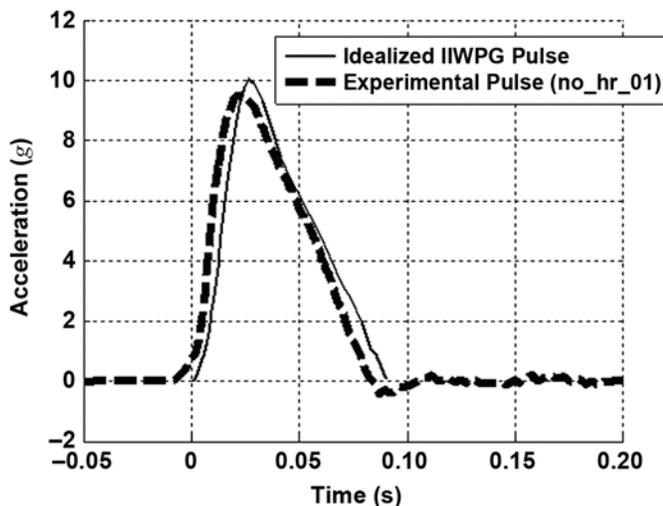


Figure 8. The 10 g 16 km/h Insurance Institute for Whiplash Prevention Group (IIWPG) rear-impact crash pulse. (Source: International Insurance Whiplash Prevention Group. IIWPG protocol for the dynamic testing of motor vehicle seats for neck injury prevention. Arlington (VA): Insurance Institute for Highway Safety; 2005) and sled acceleration measured in first test (no_hr_01). hr = head restraint.

sled acceleration measured in the first no-head-restraint test (no_hr_01). The sled acceleration in all other tests was very similar. Data were acquired at the sampling rate of 10 kHz, and the filter classes used for the sensor time histories are given in **Appendix 2** (available online only).

Wheelchair Rear Impact with No Head Restraint

In the first test with no head restraint (no_hr_01), the mechanical stop introduced to prevent damage to the dummy neck was unintentionally but fortuitously placed too far away (about 25 cm) from the head to influence the test. In the second and third tests (no_hr_02 and 03), the mechanical stop contacted the head after about 80 ms, and test results after this time must be discounted. Therefore, the first test (no_hr_01) currently best represents adult wheelchair occupant kinematics of head/neck with no head restraint, and the high-speed video images are shown in **Figure 9**.

The NIC score is calculated from the x -component accelerations of the T1 vertebra and the head COG (**Figure 10(a)**). In all three tests, the mechanical stop did not influence the peak NIC score, which occurs about 50 ms (**Figure 10(b)**). However, the influence of head contact with the mechanical stop on the NIC time history after 85 ms is clear in **Figure 10(b)** for the second and third tests (no_hr_02 and 03).

The Nkm is calculated from the upper-neck shear force (F_x) and bending moment (M_y) (**Figure 11**). The shear force remains predominantly positive throughout all three tests, and the bending moment for the first test (no_hr_01) is predominantly negative because of the unimpeded extension motion of the head, which occurred because the mechanical stop was placed too far back to contact the head. Therefore, the relevant Nkm mode is extension-posterior Nkm for the first test (no_hr_01). For the second and third tests (no_hr_02 and 03), the peak values of shear force and bending moment occur after the head contact with the mechanical stop (at 100 ms); these two tests are therefore not valid for evaluating the extension-posterior Nkm criterion. A summary of the calculated peak NIC and extension-posterior Nkm scores for the no-head-restraint tests is given in **Table 3**.

Wheelchair Rear Impact with Head Restraints

The first and second tests with head restraints (hr_01 and 02) were performed with the heavier prototype head restraint, while the third and fourth tests (hr_03 and 04) were performed with the lighter prototype. No significant

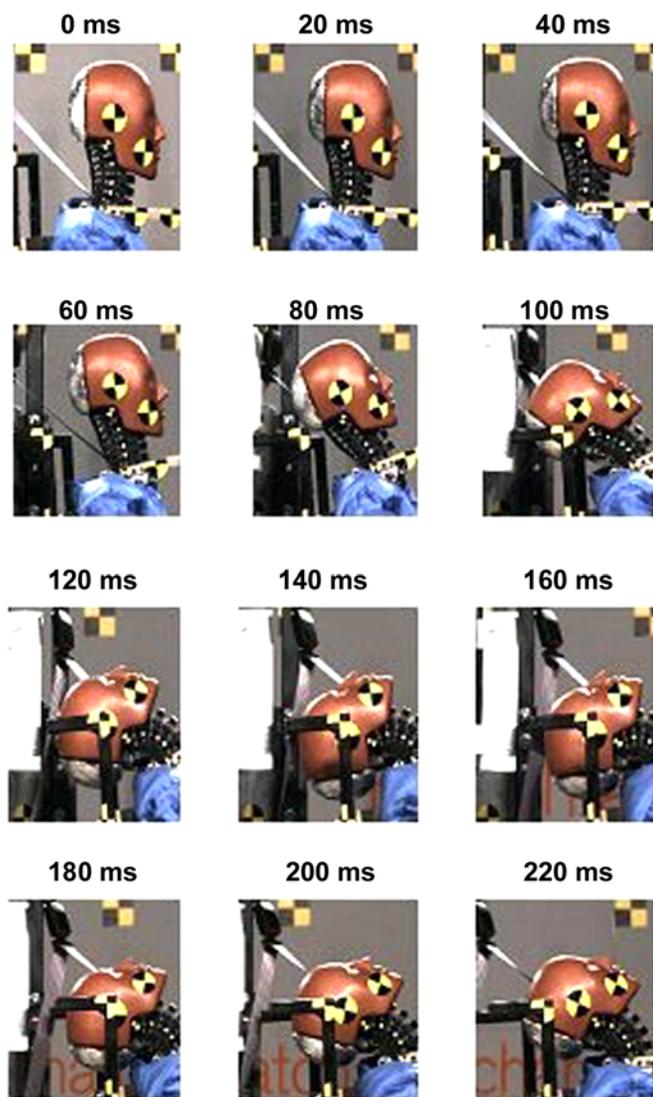


Figure 9.

High-speed video images in milliseconds of Insurance Institute for Whiplash Prevention Group Biofidelic Rear Impact Dummy II (Denton ATD Inc and Chalmers University of Technology; Gothenburg, Sweden) in rear-impact crash with use of test (no_hr_01) with reinforced surrogate wheelchair with no head restraint and no contact with mechanical stop. hr = head restraint (test code only).

bending of the head-restraint stalks was observed in any of the four prototype head-restraint tests, and therefore, results for one of the lighter prototype tests only are presented (hr_04) (Figure 12). Figure 13 shows the fifth test (hr_05) with the Rolko with no initial head/head-restraint gap. In both cases, we found no damage to the head restraint and hyperextension of the neck was prevented. Figure 14 shows the NIC for the prototype head-restraint design

(hr_04), the Rolko head-restraint (hr_05), and a no-head-restraint case (no_hr_01). Figure 15 shows the upper-neck shear force and bending moment and the resulting extension-posterior Nkm test scores for the prototype head restraint (hr_04), the Rolko (hr_05) with no gap, and no head restraint (no_hr_01). Figure 16 shows the NIC test scores for the Rolko head restraint without (hr_05) and with (hr_06) a 50 mm initial gap between the head-restraint cushion and the head. The NIC threshold and a no-head-restraint (no_hr_01) case are also shown. Injury predictions for the head-restraint tests are summarized in Table 4.

DISCUSSION

For conventional motor vehicle seats, a head restraint effectively reduces whiplash injuries to the neck in rear-impact collisions, because it substantially reduces relative motion between the occupant's head and chest [16]. For wheelchair occupants traveling in adapted vehicles, a risk of whiplash injuries also exists, either for forward-facing wheelchairs in a rear-impact collision or for rearward-facing wheelchairs in a frontal collision. However, unlike for motor vehicle seats, the provision of wheelchair head restraints is unregulated and testing of wheelchair head restraints in the mid-1990s indicated that commercial products failed in static tests through plastic bending of the vertical adjuster or pullout forces on the attachment bracket [20]. Recent sled-testing of head restraints for child wheelchair users showed that their presence significantly reduced a head-restraint head fracture, concussion, and serious neck injury risk for 12 g, 25 km/h, rear impacts [23]. However, how these findings apply to AIS1 neck injury risk for adults in lower velocity rear-impact whiplash cases is unclear. To address this problem, we performed a series of nine adult wheelchair occupant rear-impact sled tests using the 16 km/h, 10 g, IIWPG sled pulse [29], where the BioRID-II was seated in a surrogate wheelchair. Tests were performed with and without a head restraint, and a new prototype and an existing commercial head restraint (Rolko) were used.

Limitations

The sample size of the tests is small (nine tests in total) because of financial limitations. Furthermore, in the no-head-restraint tests, Thatcham Crash Laboratory required a mechanical stop to prevent damage to the neck of the dummy by limiting excessive hyperextension so that the later stages of the whiplash sequence (after about

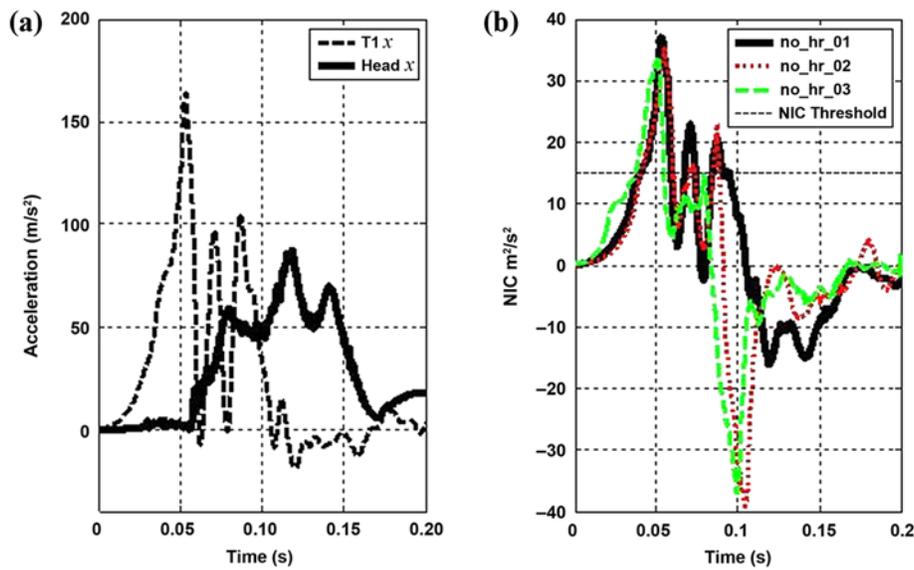


Figure 10.

(a) Thoracic (T1) and head (center of gravity) x -component accelerations for first test (no_hr_01) and (b) neck injury criterion (NIC) time histories for all three no-head-restraint tests (no_hr_01, no_hr_02, and no_hr_03). hr = head restraint (test code only).

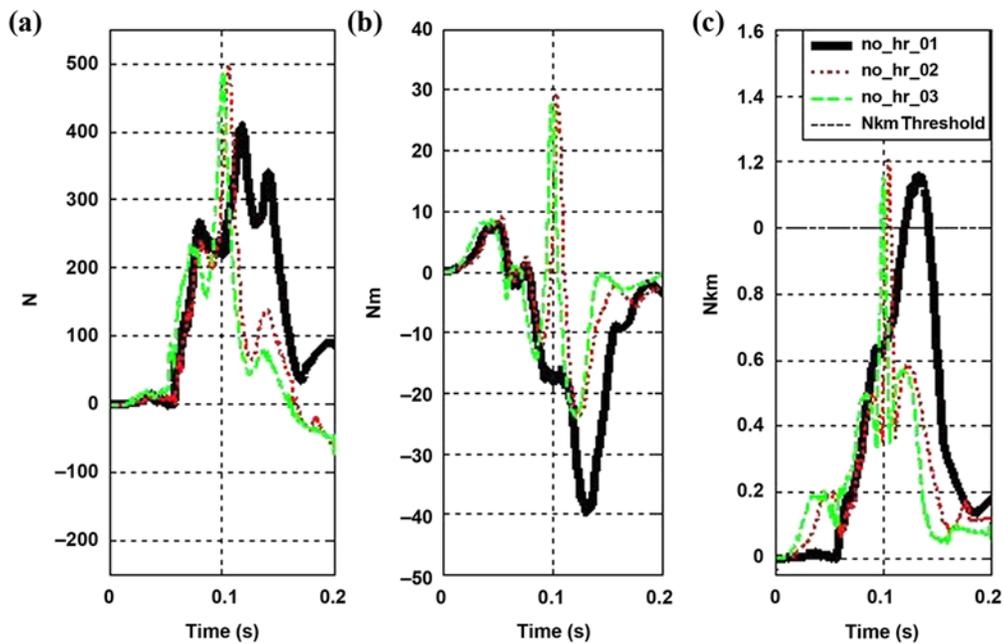


Figure 11.

(a) Upper-neck shear force (F_x), (b) bending moment (M_y), and (c) extension-posterior Nkm criterion time histories for all three no-head-restraint tests (no_hr_01, no_hr_02, and no_hr_03). hr = head restraint (test code only).

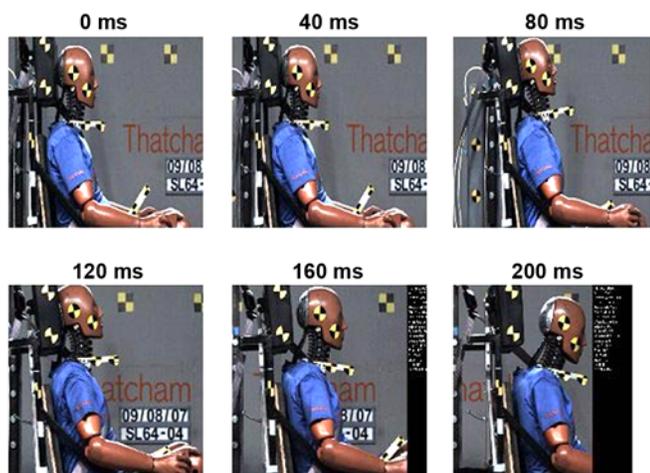
100 ms in tests no_hr_02 and no_hr_03) are invalid. However, in the first test with no head restraint (no_hr_01), the mechanical stop was incorrectly placed

and did not contact the head. Therefore, this test currently best represents head, neck, and torso kinematics for adult wheelchair occupants with no head restraint. For the

Table 3.

Peak neck injury criterion (NIC) and extension-posterior Nkm criterion values for no-head-restraint (hr) tests.

Criterion	no_hr_01	no_hr_02	no_hr_03
NIC_{max} (m^2/s^2)	37	35	34
Nkm (-)	1.16	—	—

**Figure 12.**

High-speed video images in milliseconds of Insurance Institute for Whiplash Prevention Group Biofidelic Rear Impact Dummy II (Denton ATD Inc and Chalmers University of Technology; Gothenburg, Sweden) in rear-impact crash with use of test (hr_04) with lighter prototype head restraint with no initial gap between head and head-restraint cushion. hr = head restraint (test code only).

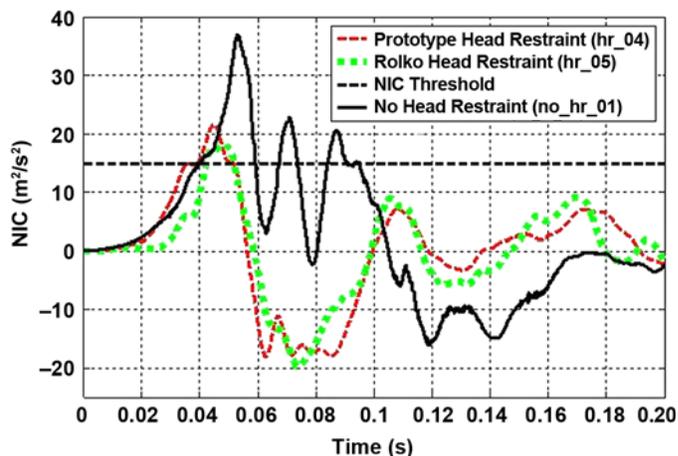
head-restraint tests, two identical tests were conducted with the lighter prototype and two with the heavier prototype, which showed good kinematic repeatability, as well as consistent extension-posterior Nkm and NIC scores (Tables 3 and 4).

The rigid design of the wheelchair used in the tests indicates that injury risks are overestimated compared with production wheelchairs with deformable seat backs [31–32]. However, the rigid wheelchair was used, since this allowed one to clearly evaluate the influence of a head restraint, irrespective of seat-back crash performance. As mentioned in the “Methods” section, we used a similar approach as Davidsson et al. [33] in validation of the BioRID-II and static evaluation of wheelchair head restraints [20]. Nonetheless, wheelchair seat-back crash-worthiness and padding materials need to be addressed separately in future research.

The biofidelity of the 50th percentile male BioRID-II model for representing wheelchair users is problematic,

**Figure 13.**

High-speed video images of Insurance Institute for Whiplash Prevention Group Biofidelic Rear Impact Dummy II (Denton ATD Inc and Chalmers University of Technology; Gothenburg, Sweden) in rear-impact crash with use of test (hr_05) with Rolko head restraint (Borgholzhausen, Germany) with no initial gap between head and head-restraint cushion. hr = head restraint (test code only).

**Figure 14.**

Neck injury criterion (NIC) for lighter prototype head-restraint design tests (hr_04) and Rolko head restraint (Borgholzhausen, Germany) (hr_05), NIC threshold (source: Böstrom O, Svensson MY, Aldman B, Hansson HA, Haland Y, Lovsund P, Seeman T, Suneson A, Saljo A, Ortengren T. A new neck injury criterion candidate based on injury findings in the cervical spinal ganglia after experimental neck extension trauma. Proceedings of the International Conference on the Biomechanics of Impact (IRCOBI); 1996 Sep 11–13; Dublin, Ireland. Zurich (Switzerland): IRCOBI; 1996. p. 123–36), and no head restraint (no_hr_01). hr = head restraint (test code only).

and our research group is currently attempting to develop more realistic computational models of wheelchair users with spinal deformities such as scoliosis [45]. However, as mentioned in the “Methods” section, the superiority of

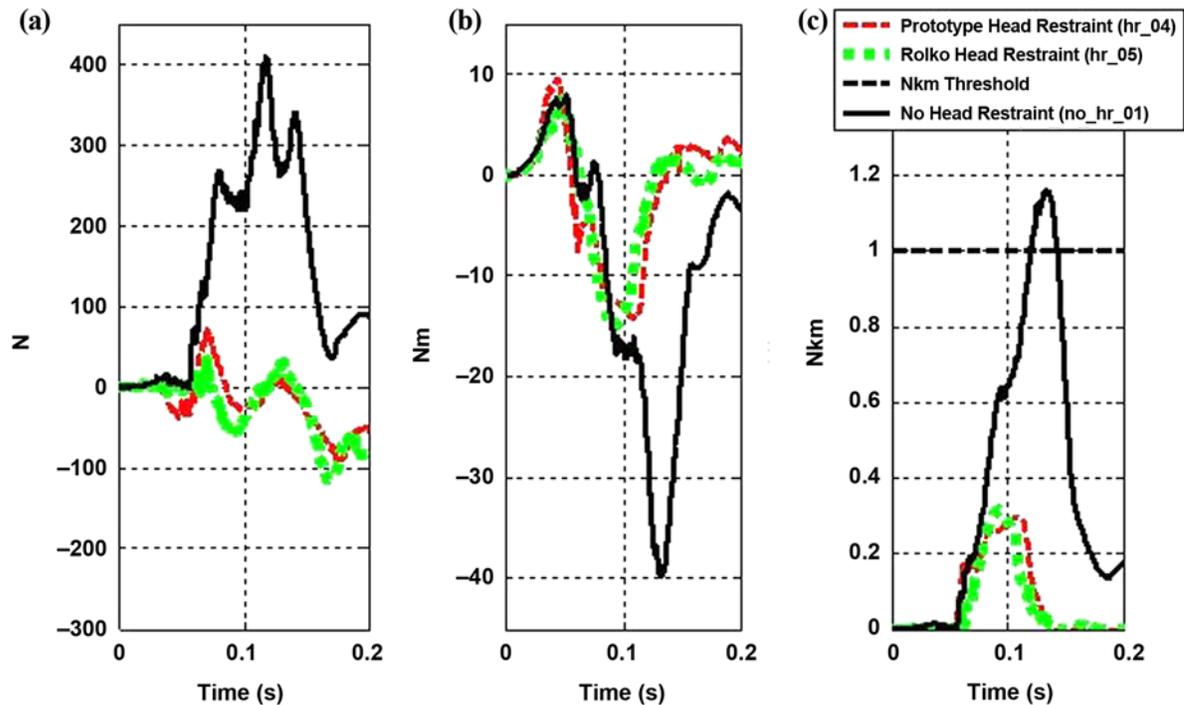


Figure 15.

(a) Upper-neck shear force, (b) bending moment, and (c) extension-posterior Nkm criterion test scores for prototype head restraint (hr_04) and Rolko head restraint (Borgholzhausen, Germany) (hr_05), Nkm threshold (*source*: Schmitt K, Muser M, Niederer P. A new neck injury criterion candidate for rear-end collisions taking into account shear forces and bending moments. Proceedings of the 17th Experimental Safety Vehicles Conference; 2001 Jun 4–7; Amsterdam, the Netherlands. Washington (DC): National Highway Traffic Safety Administration; 2001), and no head restraint (no_hr_01). hr = head restraint (test code only).

the BioRID-II over the Hybrid III and other existing dummies for rear-impact sled-test research is well-established [27–29].

Principal Results

The test series with no head restraint clearly indicates hyperextension of the neck (**Figure 9**). The peak NIC scores for these tests ranged from 34 to 37 (**Table 3**), and **Figure 7** shows that this range is associated with a >90 percent risk of neck injury symptoms persisting for >1 month. Similarly, the peak extension-posterior Nkm score for test no_hr_01 (where the mechanical stop did not contact the head and hence extension-posterior Nkm can be calculated) showed >45 percent risk of similar symptoms. One can conclude from these tests that neck injury risk for adult wheelchair occupants seated in a rigid wheelchair with no head restraint is high when subjected to a 16 km/h, 10 g, rear-impact pulse. Furthermore, although the D_v is considerably lower than for the pediatric tests of Fuhrman et al. [23], the hyperextension of the neck is qualitatively similar

in both cases. Furthermore, since research has known that yielding seat backs reduce neck loading in rear impact [31–32], the combination of either the Rolko head restraint or the prototype head restraint with a production wheelchair with a yielding seat back might sufficiently protect the neck to reduce the risk of NIC and Nkm scores to very low levels. However, further research is required to confirm this finding.

For tests with a head restraint with no initial gap between the head and head-restraint cushion, both the light and heavy version of the prototype and the Rolko showed no evidence of damage or deformation during a 10 g rear impact, and hyperextension of the neck was prevented (**Figures 12 and 13**). We observed little difference between the lighter and heavier prototype designs and, therefore, only considered the lighter prototype here for injury predictions. Evaluation of the NIC and extension-posterior Nkm showed that both the prototype and the Rolko head restraints significantly reduced injury scores compared with no head restraint (**Tables 3, 4**, and a summary in **Table 5**). Comparison of these scores with injury

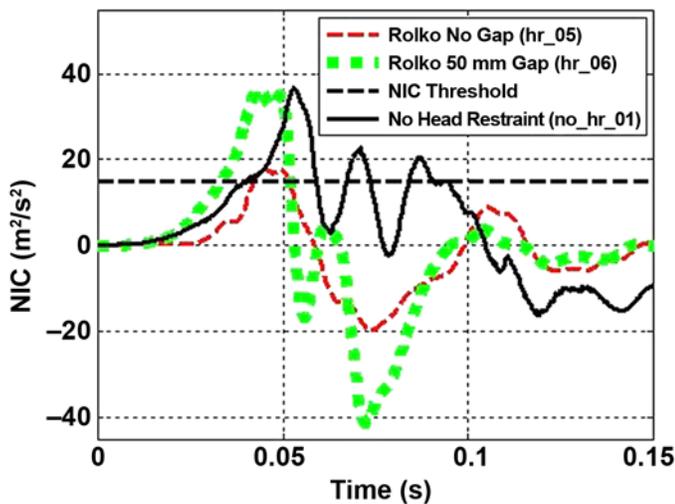


Figure 16.

Neck injury criterion (NIC) test scores for Rolko head restraint (Borgholzhausen, Germany) with (hr_05) and without (hr_06) 50 mm initial gap between head-restraint cushion and head. No head restraint (no_hr_01) and NIC threshold (*source*: Boström O, Svensson MY, Aldman B, Hansson HA, Haland Y, Lovsund P, Seeman T, Suneson A, Saljo A, Ortengren T. A new neck injury criterion candidate based on injury findings in the cervical spinal ganglia after experimental neck extension trauma. Proceedings of the International Conference on the Biomechanics of Impact (IRCOBI); 1996 Sep 11–13; Dublin, Ireland. Zurich (Switzerland): IRCOBI; 1996. p. 123–36) are also shown. hr = head restraint (test code only).

risk probabilities predicted in **Figure 7** showed that for the head-restraint tests with no head/head-restraint gap, the probability of neck injuries with symptoms lasting >1 month is reduced to about 20 to 30 percent with the NIC and to <5 percent with the extension-posterior Nkm criterion. However, considering the limitations just listed, these findings should be considered primarily as trends rather than absolute predictions.

Assessing the prototype head restraint separately from the Rolko head restraint shows some differences in the performance of the two designs when they are both tested with no initial head/head-restraint gap. The Rolko NIC score of 18.00 is lower than the average of 22.25 for the prototype head-restraint tests, while the Rolko extension-posterior Nkm score of 0.31 is higher than the average of

0.31 for the prototype design (**Table 4**). The cushion on the prototype is thicker (70 mm) than on the Rolko (about 25 mm) and also softer, probably resulting in increased rearward motion of the dummy head in the early phases (up to 80 ms) (**Figures 11** and **12**), and hence the higher NIC score for the prototype (**Figure 15(b)** and **Table 4**). Both head restraints show some dynamic rearward deflection and angular rotation of the head-restraint cushion between 0 and 80 ms (**Figures 12** and **13**), which is the critical time for the NIC. These movements are more obvious for the Rolko, and eliminating them could further reduce the Rolko NIC score in cases with no gap. However, the sample size and the nature of the tests indicate that great care is necessary in drawing conclusions from the individual crash performances of these two head restraints.

A head restraint should be placed close to the head [46]. However, for comfort reasons, research has reported for conventional motor vehicle seat users that a minimum gap of 40 to 50 mm from the head surface is necessary [12] and similar requirements apply for wheelchair users. Volunteer tests have shown that the NIC score is correlated with this head/head-restraint gap [44], and a test using the Rolko head restraint with and without a 50 mm gap between the head and head-restraint cushion confirmed this finding (**Figure 16**). In contrast, the corresponding extension-posterior Nkm score is less sensitive to the initial gap, since the shear force and bending moment components comprising the extension-posterior Nkm only approach critical values when substantial hyperextension of the neck has occurred, as can be clearly seen in the no-head-restraint tests (**Figure 16**). However, considering that we performed only one test to evaluate the influence of the gap, no definitive conclusions can be drawn, except that previous results reporting the influence of the gap on the NIC score are confirmed.

Potential for Improvements: Usability

A major requirement for a wheelchair head restraint is that it is easily adjustable, attachable, and detachable. In the prototype design, the head-restraint cushion angle and pivot arm angle adjusters (**Figure 4**) are easy to use

Table 4.

Neck injury criterion (NIC) and extension-posterior Nkm criterion scores for head-restraint (hr) tests.

Criterion	hr_01	hr_02	hr_03	hr_04	hr_05	hr_06	Threshold
NIC _{max} (m ² /s ²)	20	24	23	22	18	40	15
Nkm (–)	0.35	0.30	0.30	0.30	0.31	0.34	1

Table 5.

Neck injury criterion (NIC) and extension-posterior Nkm criterion scores for no-head-restraint and head-restraint tests with no initial gap between head and head-restraint cushion.

Criterion	No Head Restraint (<i>n</i> = 3)	Head Restraint (No Gap) (<i>n</i> = 5)	Threshold
NIC _{max} (m ² /s ²)	34–37	18–24	15
Nkm (–)	1.16	0.30–0.35	1

and require no additional tools to attach. The capability of the current prototype design to integrate with commercial wheelchairs is shown in **Figure 17**.

However, the capability of the prototype to attach to the wheelchair remains problematic in a number of cases because a small portion of the back support canvas must be cut away to allow the attachment clips to connect directly to the seat-back uprights. In contrast, the Rolko head restraint attaches to the wheelchair by clamping onto the handles of the wheelchair with thumb screws. The Rolko system is more user-friendly but might also be improved with a friction clamp-handle mechanism. Other head restraints are attached directly to the uprights of the seat back, but these are vulnerable to high pullout forces during a rear impact, as shown in Karg and Sprigle [20].

The head-restraint cushion design in the prototype is large (370 mm wide by 240 mm high) so as to support wheelchair occupants with significant spinal deformities, particularly in the rebound phase of a frontal impact.

However, the smaller cushion on the Rolko (about 230 mm wide and 100 mm high) may be aesthetically more favorable than the prototype, and the possible protective effect of the larger cushion area in the prototype remains untested. Overall, the Rolko design is significantly lighter (1.3 kg compared with 4.8 kg) and easier to use than the prototype and must be recommended because it protects the neck at a similar level as the prototype in the 10 g rear-impact tests. Investigators need to conduct further research to determine the level of neck protection that each device provides when used with production wheelchairs in a frontal vehicle impact with a rearward-facing wheelchair occupant.

CONCLUSIONS

Rear-impact sled tests (10 g, 16 km/h) of the BioRID II model seated in a rigid wheelchair with no head restraint showed that the risk of adult wheelchair user neck injuries evaluated with the NIC and Nkm injury criteria is high. By comparison, a new prototype head restraint and the commercial Rolko head restraint reduced the injury criteria scores substantially: the NIC scores for the tests with the head restraints with no gap ranged from 18 to 24 (approximately a 20%–30% chance of neck injury symptoms of duration >1 month) compared with no head restraint NIC scores of 34 to 37 (approximately a 95% chance of neck injury symptoms lasting >1 month).

**Figure 17.**

Two views of prototype head-restraint frame attached to commercial wheelchair frame.

The corresponding extension-posterior Nkm scores for the tests with the head restraints with no gap ranged from 0.30 to 0.35 (approximately 5% chance of neck injury symptoms lasting >1 month) compared with no head restraint Nkm scores of 1.16 (approximately 45% chance of neck injury symptoms lasting >1 month). However, the number of sled tests performed was small (three without a head restraint and six with a head restraint), and therefore, these results should primarily be considered as trends rather than absolute predictions. Preliminary results also show that the horizontal gap between the head and the wheelchair head-restraint cushion should be as small as possible. Both the new prototype head restraint and the Rolko head restraint performed similarly, but the Rolko is a more user-friendly product because it is lighter and can be more easily attached and removed.

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