# Development of a wheelchair headrest for rear impact protection

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## ABSTRACT
Evaluation of wheelchair headrests in the 1990s showed that commercially available products failed in static FMVSS 202 tests. However, those tests did not evaluate dynamic rear impact neck injury risk for wheelchair users. In this paper baseline testing of the BIORID dummy seated in a surrogate wheelchair subject to IIWPG rear impact tests is presented. Neck hyperextension was observed, and injury risk evaluated using the *NIC* and *Nkm* criteria showed significant risk for occupants of rigid wheelchairs with no headrest in rear impact. A prototype neck protection headrest was designed and tested and results showed that the device successfully prevented hyperextension of the neck, and large reductions in the injury scores evaluated using the *NIC* and *Nkm* criteria were observed.

**Keywords:** wheelchair occupant protection, whiplash, neck injury criterion, headrest prototype

Wheelchair-user safety research has mostly focussed on frontal impact, e.g. [1, 2], but whiplash injuries are among the most numerous and costly of crash related injuries [3]. Low severity rear impact can lead to AIS1 whiplash neck injuries. Although the precise mechanisms remain unclear, injuries result from high rate differential movement of the head relative to the torso, and can be reduced by either a high seatback or a separate headrest positioned behind and close to the occupant's head [4]. For wheelchairs in transit, a headrest was recommended over 25 years ago to prevent whiplash [5, 6], but provision of a headrest is still not mandatory. The safety level of postural head supports or dedicated headrests in current use is generally unknown since FMVSS 202 does not apply and there is no standard addressing wheelchair headrest safety. An analysis of the crashworthiness of commercially available wheelchair headrest systems using FMVSS 202 static tests in the 1990s [7] showed that all failed, either at the interface bracket with the seatback or in the seatback itself or via plastic bending in the vertical adjuster. However, they did not perform dynamic tests and the evaluation of standard neck injury criteria was therefore not possible. Very recently, nine 12-14g rear impact tests of production wheelchairs showed general failure of the seatback, and although headrests were present in two cases, head excursions always exceeded allowable limits [8]. A headrest for neck protection relies on seatback integrity as a base of support, and in this paper it is assumed that wheelchair seatback integrity is maintained. A baseline neck injury risk for occupants of a rigid wheelchair with no headrest is established using sled tests and compared to results of sled tests using a prototype headrest. For further details of the experimental protocol and subsequent in-depth analysis the reader is referred to [9].

## METHODS
Rear impact sled tests with no headrest were performed at Thatcham Crash facility using the 50%[ile] male BIORID II S1 dummy seated in a rigid wheelchair similar to the standard J2252 [10] and subjected to the 10g IIWPG pulse [11], see figure 2. A rigid wheelchair was chosen to assess only headrest influence and reduce the number of test variables. An Unwins (SWR/10, QB20/2/1200) WTORS Restraint System and vehicle rail system were used. A mechanical stop was positioned to allow considerable hyperextension of the neck but prevent damage to the dummy.

A good correlation between both the Neck Injury Criterion (*NIC*) [12] and the *Nkm* [13] criteria and real-world whiplash injuries has been observed. The *NIC* quantifies the initial retraction phase of a low-speed rear impact and is found from the X-component acceleration of the first thoracic vertebra (T1) relative to the head centre of gravity: $NIC = 0.2 \times a_{rel} + v_{rel}^2$ and the tolerance threshold is $15m^2/s^2$. The *Nkm* criterion combines upper neck shear force ($F_x$) and bending moment ($M_y$) normalised by critical values ($F_{int}$ & $M_{int}$):

$$N_{km} = \frac{|F_x(t)|}{F_{\text{int}}} + \frac{|M_y(t)|}{M_{\text{int}}}$$

Four modes are possible, and an *Nkm* score >1 in any one predicts a neck injury in that mode.

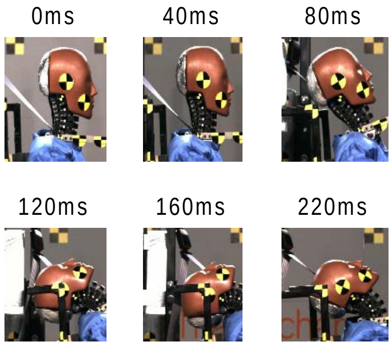

Figure 1: Time series for BIORID wheelchair rear impact test with no headrest.

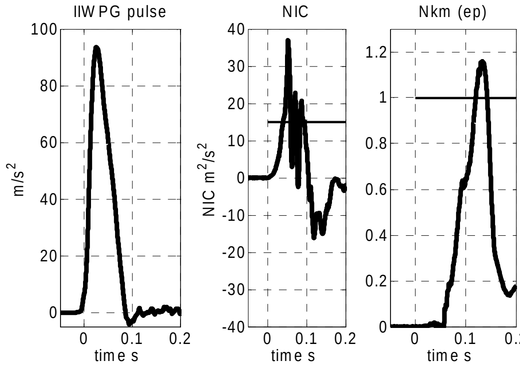

Figure 2: Sled pulse and *NIC* and *Nkm* extension posterior for no headrest tests, adapted from [9].

In the first test the mechanical stop made no contact with the head at all, and this test is the best representation of wheelchair occupant head/neck kinematics in the absence of a headrest, see figure 1. The corresponding *NIC* and *Nkm* scores show a high risk of neck injury for wheelchair occupants seated in a rigid wheelchair with no headrest when subjected to the IIWPG rear impact pulse, see figure 2. These results form a baseline risk level to which tests with a headrest can be compared.

**PROTOTYPE DESIGN**

The wheelchair headrest design focused on the following design criteria:

1. Sufficient strength to withstand a 10g rear impact without excess deformation.
2. Large contact surface to protect the neck in frontal impact rebound.
3. Minimise head impulse when contact with headrest occurs.
4. Lightweight and readily attachable/removable from wheelchair seatback.
5. Provide good neck protection in rear impact.

Preliminary Madymo simulations indicated a peak headrest load of ca. 700N for the IIWPG rear impact test using a BIORID dummy and that an early spring loaded mechanism concept greatly increased the *NIC* score. The final iteration of the headrest design attached to a commercial as well as the surrogate wheelchair is shown in figure 3. A design feature was separation of the support connections to the seatback to increase pull out and bending strength. The design was found to be compatible with some existing chairs, however, attachment problems were encountered with several other models. A light and heavy gauge version of the prototype were produced and tested.

**Results of wheelchair headrest whiplash testing**

Figure 4 shows the test with the light gauge prototype. There was no visible damage to the headrest and hyperextension of the neck was prevented. Figure 5 shows the *NIC* and *Nkm* scores for both the light and heavy gauge prototype headrest designs as well as the baseline no headrest case.

**DISCUSSION**

Testing of wheelchair headrests in the mid 1990s [7] indicated that commercially available products failed in static FMVSS 202 tests. Recent rear impact sled tests of production wheelchairs showed frequent seatback failure with consequent loss of occupant retention, and even in cases with headrests, head excursions exceeded allowable limits [8]. However, neck injury criteria such as the *NIC* and *Nkm* were not evaluated and the onset of seatback failure seriously reduces seat-integrated headrest effectiveness regardless of headrest design.


Figure 3: Prototype headrest frame attached to a commercial wheelchair frame [9].

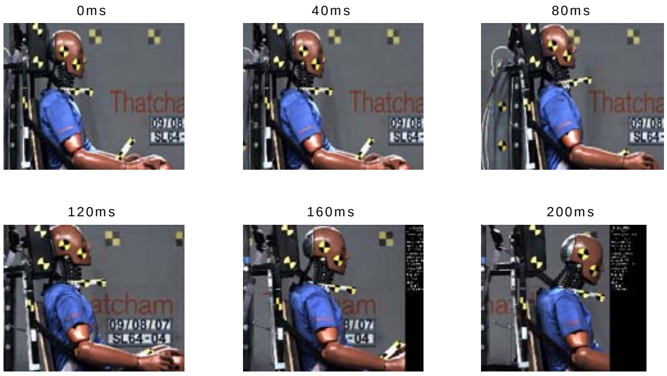


Figure 4: Whiplash test using headrest prototype.

This paper quantifies neck injury risk for occupants of rigid wheelchairs in cases with no headrest, and presents the development and testing of a prototype headrest. Hyper-extension of the neck is clear when no headrest is present (figure 1) and the corresponding *NIC* score of 37 is more than twice the injury threshold level of 15, while the *Nkm* score of 1.16 also exceeded the threshold of 1. Therefore absence of a headrest exposes rigid wheelchair occupants to a very high chance of neck injury in a 10g rear impact collision. Testing of the prototype headrest (figure 3) showed it successfully withstood the impact and prevented hyperextension of the neck (figure 4). The *NIC* and *Nkm* scores show that both a light and heavy gauge version of the prototype headrest provide large reductions in injury scores compared to the baseline (no headrest) case (figure 5). Although the *NIC* threshold level for injury is 15, and both headrests are somewhat above this score, the rigid wheelchair means that the early forces initiating torso displacement are greater than in production wheelchairs with deformable seatbacks [14]. The soft cushion on the prototype could be made harder to further reduce the *NIC* score, but this comes at the expense of a harder head/headrest contact, which may not be desirable. For very hard foams, even a small initial gap results in a hard contact between the headrest cushion and the head, while very soft foams bottom out.

A major requirement for a wheelchair headrest is to be easily adjustable, attachable and detachable. In the prototype design, the headrest cushion angle and pivot arm angle adjusters are easy to use and require no additional tools to attach. The ability of the current prototype design to integrate with commercial wheelchairs is shown in figure 3. However, the attachment to commercial wheelchairs remains problematic in a number of cases as a portion of canvass must be cut away to allow direct connection of the attachment clips to the seatback uprights. Future work will focus further on this issue.

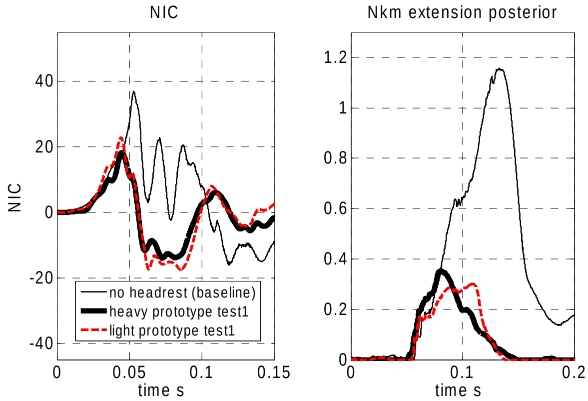

Figure 5: *NIC* and *Nkm* for prototype headrest and baseline no headrest case, adapted from [9].

## CONCLUSIONS

Rear impact sled tests with the BIORID dummy in a rigid wheelchair with no headrest showed neck injury risk evaluated using *NIC* and *Nkm* is substantially above threshold levels. A new prototype wheelchair headrest was designed and developed and tested in rear impact sled tests together. By comparison with the baseline no headrest test, both the light and heavy prototype headrest prevented hyperextension of the neck and greatly reduced the injury criteria scores to close to threshold levels.

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