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Correlation Between Neck Injury Risk and Impact Severity Parameters in Low-Speed Side Collisions

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Study Design. *In vitro* acceleration study on human cadaveric cervical spine specimens.

Objectives. To investigate the correlation between the risk to sustain a structural cervical spine injury and vehicle-related impact severity parameters.

Summary of Background Data. Impact severity parameters, such as the peak acceleration of the vehicle, its mean acceleration, and its velocity change, are often used to predict the whiplash injury risk or to objectify the patient's symptoms even though their correlation to injury is still not well understood.

Methods. In a series of three *in vitro* experiments, a total of 18 human cadaveric cervical spine specimens were subjected to incremental side accelerations until structural injury occurred. While the duration of the acceleration pulse was kept constant throughout all three experiments, its shape was varied: In Experiment I, the acceleration pulse had a fast increase up to the maximum value and a fast decrease down to zero (fast-fast). Experiment II was characterized by a slow increase and fast decrease (slow-fast), and Experiment III was characterized by a fast increase and a slow decrease (fast-slow).

Results. The specimens of Experiment II (slow-fast) sustained structural injury at a significantly higher peak acceleration of the sled (4.6 g on average) than those of Experiments I (fast-fast) (2.6 g) and III (fast-slow) (3.1 g). In contrast, mean acceleration and velocity change of the injuring impacts were almost the same in all three experiments.

Conclusion. The injury risk to the cervical spine was predictable by the mean acceleration of the sled and since the duration of the crash pulses was constant also by its velocity change but not by its peak acceleration.

Key words: whiplash trauma, cervical spine, injury criterion, impact severity, biomechanics, *in vitro* experiment. **Spine 2004;29:2404–2409**

The whiplash trauma of the cervical spine is one of the most common injuries in traffic accidents. Despite the high vehicle safety standards, its incidence is still rising.[1] Whiplash injuries therefore continue to represent a substantial societal problem worldwide with associated costs, which are estimated at $4.5 billion to $10 billion annually in the United States,[2–4] at €1 billion annually in Germany,[5] and in average at over CAD $3800 per whiplash subject in Quebec.[6]

In the absence of objective medical findings, impact severity parameters such as the peak acceleration, mean acceleration, or velocity change (δ-v) of the vehicle often are used to indirectly assess the whiplash injury risk or to objectify the patient's symptoms. Compared with occupant-related injury criteria such as the neck injury criterion (NIC), the shear force and bending moment criterion Nkm, or the neck displacement criterion (NDC),[7–9] they have the big advantage that they can much more easily be determined. The only data that have to be known are the acceleration-time history of the vehicle. This is the case in most experimental studies, and since an increasing number of insurance companies are equipping their covered cars with crash-pulse recorders[10–14] in more and more real-life crashes. And even if the acceleration-time history of a car involved in a real-life crash has not directly been recorded, peak acceleration, mean acceleration, and velocity change can in most cases *ex post* be reconstructed if at least the deformation of the car is known.

However, to date, this advantage of the vehicle-related parameters is only of little value because, unfortunately, there is still much debate about their correlation with the whiplash injury risk. In some experimental studies, the parameter δ-v significantly correlated with the injury risk,[15–17] in others the risk was more influenced by a change of acceleration,[18–20] and in real-life crashes the mean acceleration better explained the risk of whiplash than the parameter δ-v did.[10–14] Despite these partially inconsistent results, injury thresholds have been defined for each of these parameters.[16,17,21,22] Their use, however, might lead to a completely incorrect assessment of the patients.

The aim of the present in vitro study therefore was to investigate the correlation between the risk to sustain a structural cervical spine injury and the peak acceleration, mean acceleration, and velocity change of the vehicle.

Materials and Methods

In a custom-made pneumatic acceleration apparatus,[23] a series of three *in vitro* acceleration experiments was carried out. For each of the three experiments, six fresh frozen human cadaveric cervical spine specimens, including the occiput (C0) and the first thoracic vertebra (T1), were selected according to their

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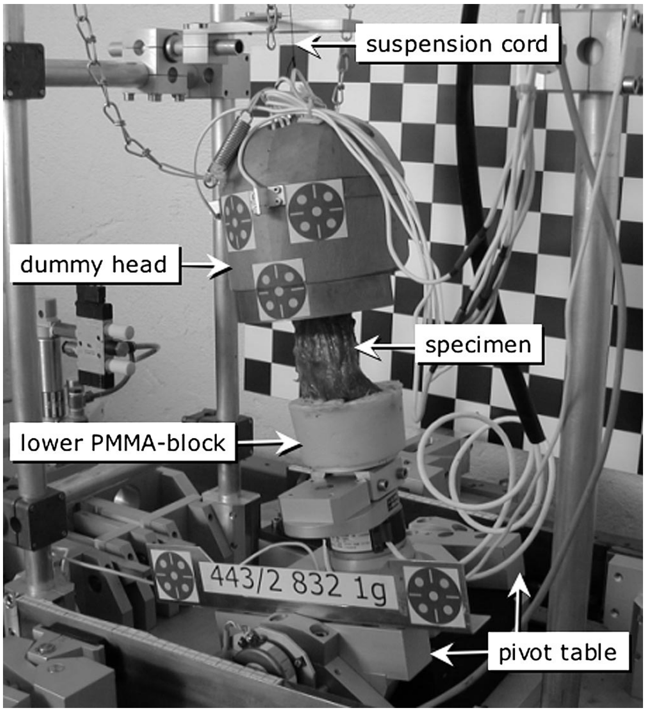


Figure 1. In the custom-made pneumatic acceleration apparatus, the lower end of the specimens was fixed to a damped pivot table. On the occipital bone a dummy head was mounted, which had to be balanced with a suspension cord. This cord was cut at the beginning of each impact.

radiographic and macroscopic appearance. Exclusion criteria were spinal disorders except for minor degeneration. The age of the donors only served as a secondary selection criterion an finally was in mean 80 years in Experiment I, 81 years in Experiment II, and 81 years in Experiment III. This morphology-based selection procedure was chosen since it allows application of the results to younger specimens better than a primarily age-based selection.

Before testing, the specimens were thawed at 4°C, and all soft tissue surrounding the discoligamentous spine was carefully removed. C0 and T1 were embedded in polymethylmethacrylate (PMMA) attaching importance to a physiologic alignment of the specimen. Then the lower PMMA block was fixed to the acceleration sled *via* a damped pivot table that was allowed to pivot passively around an axis perpendicular to the direction of the acceleration (Figure 1). This pivoting movement accounted for the passive movements of the trunk during collision.

A dummy head (mass 4.5 kg,[24] physiologic position of the center of gravity[25]) was fixed on the PMMA block on C0 in order to guarantee adequate inertia. Before acceleration, the dummy head was balanced using a suspension cord. At the beginning of each acceleration, this suspension cord was cut to allow the head to move completely unconstrained.

In all three experiments, each specimen was subjected to a series of incremental 90° side collisions from the right, which all lasted approximately 120 milliseconds. The first impact was characterized by a peak acceleration of the sled of approximately 1 g. In each following impact, this acceleration was increased by another 1 g. The experiment was stopped as soon as any structural failure became macroscopically visible.

The three experiments only differed in the shape of the acceleration curve of the sled (Figure 2). In Experiment I, the acceleration curve of the sled had an almost rectangular shape with a fast increase up to the maximum value, a plateau and a fast decrease down to zero (fast-fast). In Experiment II the acceleration curve of the sled had a more triangular shape with a slow increase up to the maximum value and a directly following fast decrease down to zero (slow-fast). Similarly, in Experiment III, the shape was more triangular but in contrast to Experiment II, the increase up to the maximum value was fast and the directly following decrease down to zero slow (fast-slow).

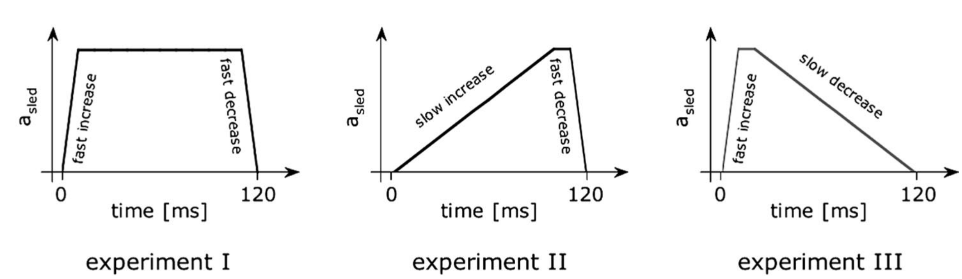
During the impact, the acceleration-time history of the sled was recorded for two seconds (EGE-73AE1–100D1, Entran, Ludwigshafen, Germany). According to SAE J211 and DIN ISO 6487, presample low-pass filtering was carried out at a cutoff frequency of 250 Hz. Then data were sampled at a rate of 9.6 kHz and digitally low-pass filtered to fit the channel amplitude class CAC 60. These data finally were used to determine the three impact severity parameters peak acceleration, mean acceleration, and velocity change (Figure 3).

Statistical comparisons were made between the three experiments to characterize the effect of the crash pulse shape on the three impact severity parameters. For this purpose, the Kruskal-Wallis test and the exact Wilcoxon signed rank test for paired comparisons were used at a 5% significance level. All *P* values were subjected to a Bonferroni-Holm correction for multiple comparisons.

■ Results

All except for two specimens sustained a rupture of the left facet joint capsule (impact from the right) and the

Figure 2. Schematic sled acceleration curves. In Experiment I, the sled acceleration curve (a_{sled} *vs.* time) had a fast increase up to the maximum value and a fast decrease down to zero (fast-fast). In Experiment II, the acceleration curve was characterized by a slow increase and a fast decrease (slow-fast) and in Experiment III by a fast increase and a slow decrease (fast-slow). In all three experiments, the duration of the acceleration pulse was approximately 120 milliseconds.



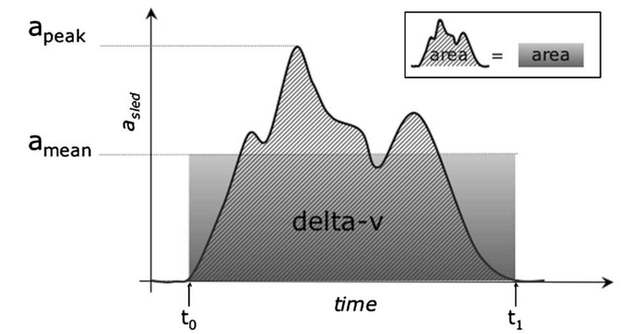


Figure 3. Schematic illustration of the impact severity parameters, which were evaluated in this study: peak acceleration (a_{peak}), mean acceleration (a_{mean}), and change of velocity (δ-v), which corresponds to the area below the acceleration curve. All parameters refer to the acceleration pulse of the sled (a_{sled}) between its beginning t_0 and its ending t_1.

intervertebral disc in one of the segments C4–C5, C5–C6, C6–C7, or C7–T1 (Table 1). In some cases, an additional partial rupture of the right facet joint capsule and/or an additional fracture of the right articular process of one of the adjacent vertebrae was observed. One of the other two specimens sustained a complete rupture at C6–C7 including both joint capsules, the intervertebral disc, and all ligaments and the other one a partial rupture of the left facet joint capsule without involvement of the disc. These two specimens were excluded from evaluation, since the kind and extend of the injury had to be kept as constant as possible throughout all specimens. Otherwise, the crash pulse shape would not have been the only influencing variable in comparing the three experiments and differences between them could have also been attributed to differences in the kind and extend of injury.

The specimens of Experiment II (slow-fast) failed at a significantly higher peak acceleration (4.6 g on average) than those of Experiment I (fast-fast) (2.6 g) and III (fast-slow) (3.1 g) ($P < 0.05$, Wilcoxon signed rank test) (Figure 4, Tables 1, 2). In contrast, mean acceleration and velocity change at failure were almost the same in all three experiments ($P > 0.05$, Kruskal-Wallis Test).

Discussion

The three vehicle-related impact severity parameters tested in this study differently correlated to the risk to sustain a structural cervical spine injury:

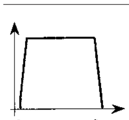
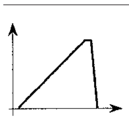
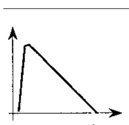
Peak Acceleration

Depending on the shape of the crash pulse, the structural injury occurred at significantly different peak accelerations of the sled (Figure 4, Tables 1, 2). This finding corresponds well with a study on rear-end collisions published by Krafft *et al.*[12] In a comparison between crash pulse recordings and neck injury outcome, the authors were able to show that in most of the occupants who sustained symptoms the peak acceleration varied considerably between 2.7 and 14.7 g. These results indicate that the peak acceleration of the vehicle should not be used to predict the whiplash injury risk.

Velocity Change and Mean Acceleration

In contrast to the peak acceleration of the sled, which significantly varied in the injuring impacts depending on

Table 1. Peak Acceleration (a_{peak}), Mean Acceleration (a_{mean},) and Velocity Change (delta-v) of the Sled During the Injuring Impacts

experiment I	specimen no.	gender	age [years]	a_{peak} [g]	a_{mean} [g]	delta-v [km/h]	injured segment
 fast - fast	I-1	f	86	2.3	1.7	7.7	C5–6
	I-2	m	67	2.3	1.7	7.7	C5–6
	I-3	f	91	2.4	1.8	8.0	C6–7
	I-4	f	87	2.4	1.8	8.2	C7–T1
	I-5	m	72	3.7	2.8	12.6	C7–T1
	I-6*	m	74	–	–	–	–
experiment II	**specimen no.**	**gender**	**age [years]**	**a_{peak} [g]**	**a_{mean} [g]**	**delta-v [km/h]**	**injured segment**
 slow - fast	II-1	f	87	4.0	1.1	8.2	C7–T1
	II-2	f	92	4.7	2.8	11.4	C6–7
	II-3	f	87	5.6	2.6	11.6	C6–7
	II-4*	f	85	–	–	–	–
	II-5	f	74	4.3	1.3	9.5	C6–7
	II-6	m	59	4.6	1.3	8.7	C6–7
experiment III	**specimen no.**	**gender**	**age [years]**	**a_{peak} [g]**	**a_{mean} [g]**	**delta-v [km/h]**	**injured segment**
 fast - slow	III-1	m	92	3.0	1.5	7.1	C5–6
	III-2	f	87	3.0	1.6	6.9	C5–6
	III-3	f	81	3.2	1.7	8.2	C6–7
	III-4	f	75	2.1	1.1	5.2	C5–6
	III-5	f	79	4.1	2.2	10.5	C4–5
	III-6	f	72	3.0	1.9	7.7	C6–7

* These two specimens had to be excluded from evaluation since their structural injury was not comparable to that of the other specimens.

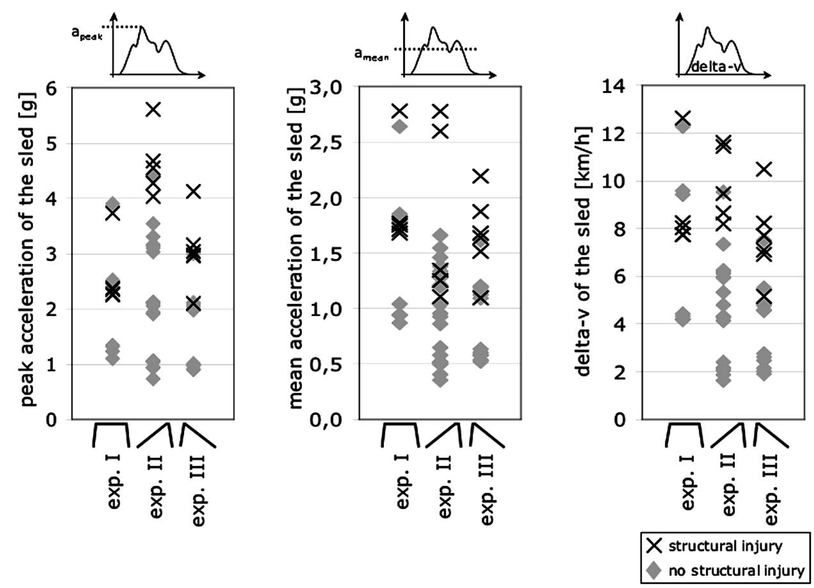


Figure 4. Peak acceleration, mean acceleration, and velocity change (δ-v) of the sled during the impacts, which caused structural injury (black crosses) and during those, which did not (gray rectangles).

the shape of the crash pulse, the mean acceleration, and the velocity change did not (Figure 4, Tables 1, 2). Thus, in this study, both mean acceleration and velocity change were suitable to predict the risk to sustain a structural cervical spine injury. In the literature, a good correlation between velocity change and neck injury risk has also been reported by Siegmund *et al* following a series of volunteer tests.[15] However, in the present study as well as in that of Siegmund *et al*,[15] the duration of the crash pulses did not significantly vary. For consequence, velocity change and mean acceleration were mathematically almost proportional to each other, or, in other words, either both parameters or neither has to be expected to correlate with the neck injury risk. In reality, however, the crash pulses significantly vary in duration.[14,26] Thus, velocity change and mean acceleration might be related to the whiplash injury risk in completely different ways and to completely different degrees. This assumption is supported by an experimental study on rear-end impacts conducted by Linder *et al* who were able to show that the same δ-v produced with different peak and mean accelerations generated very different dummy responses[19] and by several studies that all observed that the mean acceleration probably better explains the risk of whiplash than the parameter δ-v does.[10–13] Therefore, if the duration of the crash pulse is unknown or if it varies from impact to impact, the mean acceleration rather than the velocity change should be used to predict the whiplash injury risk.

Limitations

The following limitations should be taken into account in order to draw the right conclusions:

This study acts on the assumption that whiplash is caused by a physical overloading of the cervical spine. Even though many researcher agree with this assump-

Table 2. Mean (±SD) and Median (With Range) Peak Acceleration (a_{peak}), Mean Acceleration (a_{mean},) and Velocity Change (delta-v) of the Sled During the Injuring Impacts. P-values Calculated With the Kruskal-Wallis Test and if Needed With the Wilcoxon Test. The Significance Level Was Set to 5%. All p-values Are Corrected for Multiple Comparisons

a_{peak} [g]	Mean	SD	Med	Min	Max	Kruskal-Wallis Test	Wilcoxon Test
experiment I	2.6	0.6	2.4	2.3	3.7		0.0351
experiment II	4.6	0.6	4.6	4.0	5.6	0.0225	0.0387; > 0.05
experiment III	3.1	0.6	3.0	2.1	4.1		
a_{mean} [g]	Mean	SD	Med	Min	Max	Kruskal-Wallis Test	Wilcoxon Test
experiment I	1.9	0.5	1.8	1.7	2.8		
experiment II	1.8	0.8	1.3	1.1	2.8	>0.05	–
experiment III	1.7	0.4	1.7	1.1	2.2		
delta-v [km/h]	Mean	SD	Med	Min	Max	Kruskal-Wallis Test	Wilcoxon Test
experiment I	8.9	2.1	8.0	7.7	12.6		
experiment II	9.9	1.6	9.5	8.2	11.6	>0.05	–
experiment III	7.6	1.7	7.4	5.2	10.5		

tion, others hypothesize that the neck muscles[27] or the cervical nerve roots[7] are the primary site of injury, and some even assume that whiplash mainly is a psychologic[28] or societal[29] problem, which is not or only to a minor degree related to any physical injury.

Vehicle-related impact severity parameters do not directly reflect the mechanical loading of the occupant. To span this gap, occupant-related injury criteria have been defined such as the NIC,[7] the Nkm criterion,[8] or the NDC.[9] The NIC is calculated from the velocity and acceleration of the head relative to T1 and is based on the assumption that the fluid flow within the spinal canal causes pressure gradients that are injurious to the nerve roots. Nkm is based on upper neck flexion-extension moment and shear force and the NDC is based on the angular and linear displacement response of the head relative to T1. Even though these parameters allow a direct assessment of the loading of the occupant they have one significant disadvantage: They can only be determined if the occupant is equipped with accelerometers or load cells, or, in other words, they cannot be reconstructed after real-life crashes. In contrast to vehicle-related impact severity parameters, the occupant-related ones are therefore unsuitable to contribute to a more objective assessment of patients.

The neck muscles could not be taken into account in this *in vitro* study. Their effect during impact mainly consists of a passive and an active stabilization of the cervical spine. While the passive stabilization permanently acts, the active stabilization depends on a certain reaction time. In low-speed rear-end collisions with volunteers, Magnusson *et al* found that the average reaction time of deep and superficial neck muscles ranged between 73 milliseconds and 175 milliseconds referred to the beginning of the movement of the sled.[30] Even if it is assumed that another 100 milliseconds are needed until efficient muscle tension is developed, single muscle fibers would already actively stabilize the cervical spine during the phase of maximum stress and strain, which, in the present study, occurred approximately 150 milliseconds after the onset of the acceleration pulse. Provided that the muscles only affect the magnitude but not the quality of the kinetic and kinematic response of the neck and head, the correlations between impact severity and injury risk made in this study are transferable to reality.

All three experiments were focused on side collisions. Rear-end impacts have not been investigated. However, since the kind (soft tissue injury) and localization (lower cervical spine) of the injury were similar to those reported for *in vitro* rear-end collisions,[22] the impact severity parameters, which are predictive in side collisions most probably also are predictive in rear-end collisions.

In the present study, the risk to sustain whiplash injury was measured in terms of the occurrence of macroscopically visible structural cervical spine injuries even though, in reality, whiplash is characterized by an absence of such lesions. Nevertheless, this approach is justifiable since structural injuries are assumed to be preceded by polysegmental functional injuries, which on their part often are made responsible for the patient's symptoms.[22,31]

The age of the specimens was high compared with the age of the average whiplash patient. Physiologic age-related changes of the mechanical behavior of human tissue may therefore have altered the results in an unknown way and to an unknown degree. Nevertheless, the results may still cautiously be transferable to younger adults since specimens with macroscopically or radiologically visible spinal disorders, including moderate to major degeneration, have been excluded from this study.

■ Conclusions

The only vehicle-related impact severity parameter, which well correlates with the whiplash injury risk, is the mean acceleration. This parameter can therefore be used to predict the whiplash injury risk. The velocity change δ-v of the vehicle should only be used to predict the whiplash injury risk if the duration of the crash pulse is known or if it dos not vary from impact to impact. The peak acceleration of the vehicle should, if possible, not be used to predict the whiplash injury risk since the correlation of this parameter with the whiplash injury risk is strongly influenced by the shape of the crash pulse. Since this study was conducted on cadaveric cervical spine specimens, the absolute values of failure should not be used to define any injury thresholds for real vehicle crashes.

■ Key Points

- The correlation between the risk to sustain a structural cervical spine injury and vehicle-related impact severity parameters (peak acceleration, mean acceleration, and velocity change of the vehicle) was investigated.
- Three *in vitro* acceleration experiments were carried out, each characterized by a specific shape of the acceleration curve of the sled.
- Depending on the shape of the acceleration curve, the specimens sustained injury at significantly different peak accelerations of the sled but at almost equal mean accelerations and velocity changes.
- The injury risk to the cervical spine was therefore predictable by the mean acceleration of the sled, and since the duration of the crash pulses was constant, also by its velocity change but not by its peak acceleration.

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