

## **Seatback Rotational Control Reduces Whiplash Injury Potential: A Preliminary Computational Study**

J. B. Fice, J. S. Blouin, and G. P. Siegmund

*This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.*

### **ABSTRACT**

*Passive mechanical systems have been used in automotive seat design to reduce whiplash injuries, but these designs can only be optimized for a small range of occupant mass and impact severity. The overall goal of this work is to develop an actively controlled car seat that can reduce injurious kinematics during a rear impact for a large range of occupant mass and impact severity. In this study, feed-forward control of the seatback rotation was simulated to quantify the potential reduction in occupant kinematics that could be achieved with an active feedback controlled seat. These simulations consisted of a finite element model of a simplified automotive seat and a Hybrid III crash test dummy. Seatback rotation as a function of time was parameterized and then optimized to reduce the T1 acceleration of the dummy. Separate optimizations were performed for impact severities of 8, 12, and 16 km/h. Compared to control conditions, the optimum seatback rotation profiles reduced peak T1 accelerations by approximately 58% for the three crash pulses.*

### **INTRODUCTION**

**B**etter seat designs represent one method of reducing or preventing whiplash injuries in rear-end car collisions. Several manufacturers have developed and implemented improved seats, including Volvo's WHIPS seat, Toyota's WIP seat, Saab's RHR, and General Motors' high retention seat (Jakosson, et al., 2000; Sekizuka, 1998; Wiklund & Larsson, 1997; Viano, 2008). These designs use a combination of passive mechanical systems, improved geometry and improved materials to engage the occupant's torso and head during an impact to reduce the loads and strains experienced by the neck. Field studies have shown that these designs can reduce the risk of whiplash injury by 21 to 50% (Jakobsson et al., 2008; Kullgren & Krafft, 2010). The passive nature of these designs, however, means that they were designed for a small range of occupant mass and impact severities, and as a consequence are not able to protect all occupants equally (Kullgren & Krafft, 2010).

The overall goal of this project is to develop an active car seat that adapts seatback hinge and cushion properties to occupant mass and vehicle acceleration during a rear-end impact (Figure 1). The first



Figure 1: Prototype of the active seat.

step of this project is to use feed-forward control of these seatback characteristics with an anthropomorphic test device (ATD). The next step will be to develop and implement feedback control, again with an ATD as the occupant. Finally, a feedback control study with volunteers will be performed.

The specific goal of this study was to simulate a simplified version of the proposed seat to quantify the potential reduction in occupant kinematics that could be achieved with a feedback controlled seatback. The simulations consisted of finite element modeling of a Hybrid III ATD sitting in a simplified car seat. The feed-forward control of the seatback rotations was optimized to reduce to the acceleration at the base (T1 vertebra) of the dummy's neck.

## METHODS

A model of the Hybrid III ATD (LSTC, Livermore, CA) and a simplified model of a production automotive seat (Romilly & Skipper, 2005) were solved using LS-Dyna explicit finite element solver (LSTC, Livermore, CA; Figure 2). The seat and head restraint models used beams and discrete elements to model the frame and springs, and solid elements for the seatback foam. The seat pan was composed of rigid shells. For a complete description of the seat model used in this study please refer to Romilly & Skipper (2005).

For this analysis, we parameterized the feed-forward control of the seatback rotational velocity and then explored the reductions in occupant kinematics that could be achieved with different rotational velocity profiles. The seat pan and seatback were de-coupled and given the same horizontal linear acceleration input representing the collision pulse, but different angular inputs. No rotation was applied to the seat pan, whereas a prescribed rotational velocity was applied to the seatback by defining three points connected by a cubic hermite spline (Figure 3). The three points captured the seatback's initial rotational behavior, peak rotational velocity and rebound rotational velocity. These points were defined by five parameters and one constant: the time ( $x_1$ ) and magnitude ( $y_1$ ) of the initial rotational velocity, the time ( $x_2$ ) and magnitude ( $y_2$ ) of the peak rotational velocity, the magnitude of the rebound rotational velocity ( $y_3$ ), and a constant time for the peak rebound velocity of 120 ms (Figure 3).

The five parameters defining the seatback rotational velocity were optimized to find the minimum peak resultant T1 acceleration. The optimization was performed in LS-OPT (LSTC, Livermore, CA) using a d-optimal design of experiments with 120 runs, fitting a response surface to the results, and then finding a local minimum. The response surface had five main terms, five squared terms, and ten one-way interactions. LS-OPT utilized a leap-frog algorithm for constrained optimization (LFOPC) to find the local minimum (Snyman, 2000; Stander et al., 2012). Limits on the variables were specified to produce feasible seatback rotations that maintained contact between the dummy and seatback (Table 1). The optimized results were compared to a control condition that represented the seatback performance when the seatback and seat pan were coupled normally with a spring (Romilly & Skipper, 2005). To assess the contribution of each variable to the T1 acceleration, a global sensitivity study was carried out using the method described by Sobol, which uses a Monte-Carlo based approach to determine the total effect, including interactions, for each variable (Stander et al., 2012; Sobol, 1993).

Optimizations were performed for three different crash pulses, starting with the IIWPG 16 km/h pulse (IIHS, 2008), and then scaling the amplitude of this pulse to speed changes of 8 and 12 km/h while leaving the acceleration pulse duration fixed at 90 ms. These impact severities were chosen because they represent a range of whiplash injury risks according to epidemiologic data (Krafft et al., 2005).

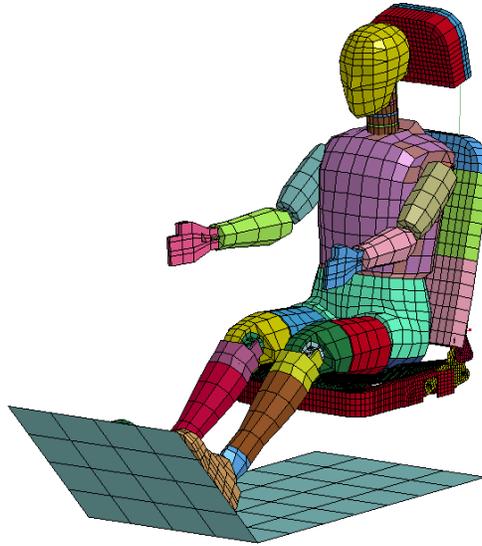


Figure 2: Model description.

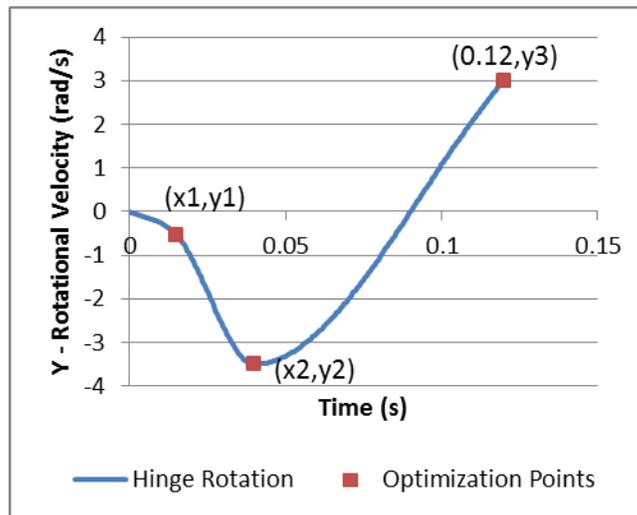


Figure 3: Example of seatback hinge rotation as a function of time.

Table 1. Variable limits for optimization.

	8km/h		12km/h		16km/h	
	min	max	min	max	min	max
<b>x1</b> (s)	0.010	0.034	0.010	0.034	0.010	0.034
<b>y1</b> (rad/s)	-0.80	0.00	-0.90	0.00	-1.0	0.00
<b>x2</b> (s)	0.035	0.10	0.035	0.10	0.035	0.10
<b>y2</b> (rad/s)	-3.0	0.0	-4.0	0.0	-5.0	0.0
<b>y3</b> (rad/s)	0.00	3.0	0.00	4.0	0.00	5.0

## RESULTS

The coefficients of determination ( $R^2$ ) for the quadratic response surface fits of T1 acceleration to the simulation results were 0.76, 0.71 and 0.63 for the 8, 12 and 16 km/h impacts respectively. The residuals for each model were well behaved, which showed that an appropriate model for optimization was selected.

In the control case, wherein the seatback hinge spring controlled seatback rotation, the T1 resultant peak accelerations of the dummy were 66, 109 and 167  $m/s^2$  for the 8, 12 and 16 km/h impacts respectively (Figure 4). After optimizing the feed-forward control of the seatback rotation, the T1 resultant peak accelerations were reduced to 28, 44 and 66  $m/s^2$  for the same impacts (Figure 4) and represented reductions of 59, 57 and 58% respectively.

To achieve these reductions in T1 resultant acceleration, the optimized peak seatback rotational velocity was delayed in time and increased in magnitude ( $x_2$  &  $y_2$ ) when compared to the control case for each of the three impact severities (Figure 5; Table 2). Also, the rebound rotational velocity ( $y_3$ ) was reduced to zero, and the timing of the initial rotational velocity ( $x_1$ ) was delayed for each impact severity. The magnitude of the initial rotational velocity ( $y_1$ ) was reduced a small amount for the 8km/h & 12km/h impacts, but it was almost double for the 16km/h impact.

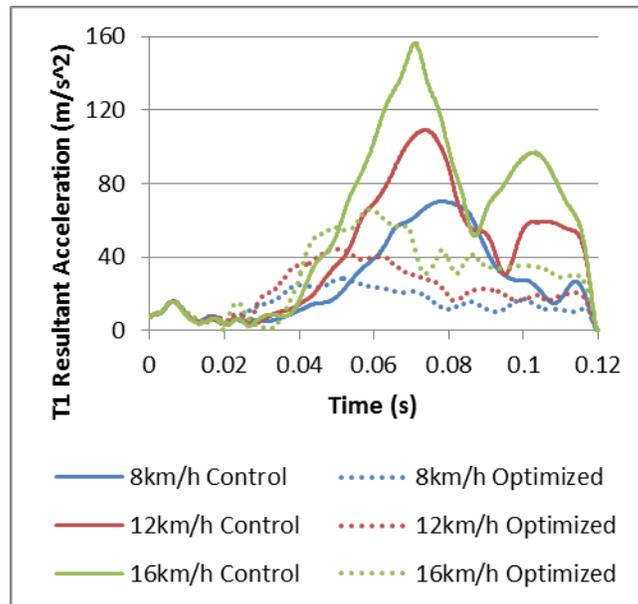


Figure 4: T1 resultant acceleration of the dummy for the control and optimized impacts.

Table 2. Variable limits for optimization.

	8km/h		12km/h		16km/h	
	Control	Optimized	Control	Optimized	Control	Optimized
<b>x1</b> (s)	0.015	0.010	0.015	0.010	0.015	0.010
<b>y1</b> (rad/s)	-0.27	-0.18	-0.40	-0.38	-0.53	-1.0
<b>x2</b> (s)	0.040	0.10	0.040	0.10	0.040	0.10
<b>y2</b> (rad/s)	-1.7	-2.8	-2.7	-4.0	-3.5	-5.0
<b>y3</b> (rad/s)	1.0	0.0	2.0	0.0	3.0	0.0

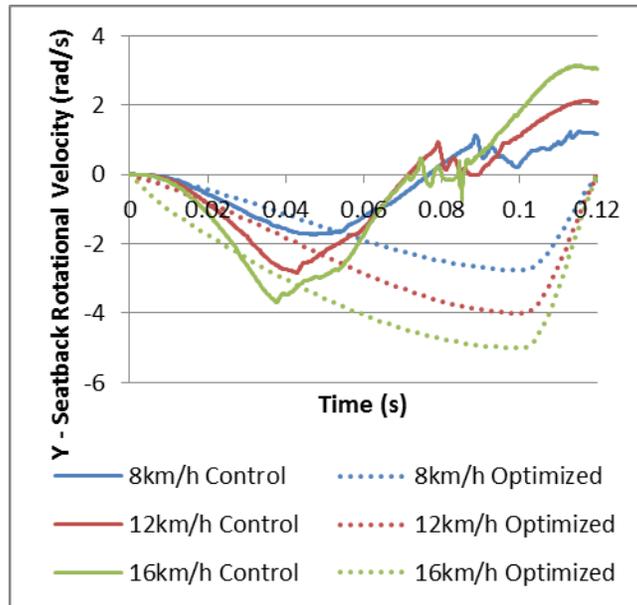


Figure 5: Seatback rotational velocity profiles of the control and optimized impact simulations

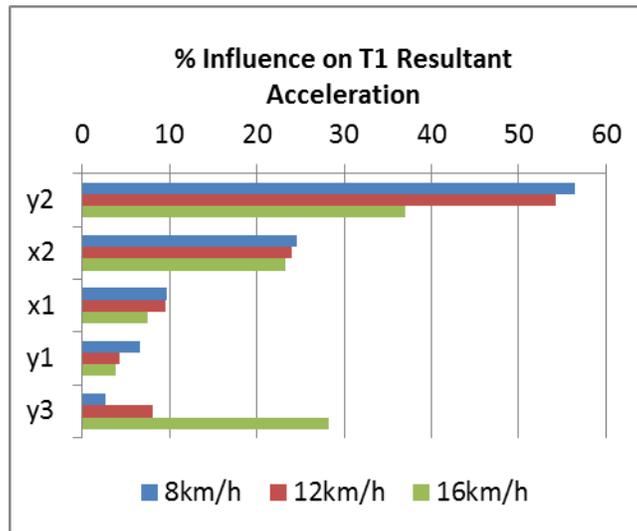


Figure 6: Global sensitivity analysis of the seatback rotational velocity variables.

The global sensitivity analysis revealed that the magnitude of the peak seatback angular velocity ( $y_2$ ) was the most influential parameter affecting T1 resultant acceleration of the dummy (Figure 6). The sensitivity to rebound velocity of the seatback ( $y_3$ ) was seen to increase with increasing impact severity. The timing of the peak rotational velocity ( $x_2$ ) was the second most important variable for the 8 km/h & 12 km/h impacts, and third most for the 16 km/h impact. The timing and magnitude of the initial seatback rotational velocity ( $x_1$  &  $y_1$ ) had relatively small influences on T1 resultant acceleration for the three impact severities investigated.

## DISCUSSION

Optimized feed-forward control of seatback rotation as a function of time reduced the T1 acceleration of a Hybrid III ATD sitting in a simplified finite element model of an automotive seat for rear impacts of 8, 12 and 16 km/h. Reduced T1 accelerations would likely reduce the loads and strains in the neck tissues and would be expected to reduce the risk of whiplash injury. This preliminary computational study provided evidence that an actively controlled car seat could result in large reductions in neck loads and provides the basis to proceed with an experimental testing of a prototype seat. Moreover, this work will guide the experimental work by providing input parameters that can be applied directly to control the seat hinge motors in the prototype active seat. For example, the rotation or moment of the seat hinge as a function of time can be easily measured from the optimized simulations and then used to control the seat hinge during experimental sled impacts. In future work, this model could also help define the feedback control for the prototype.

The T1 acceleration of the dummy was most sensitive to changes in the peak rotational velocity of the seatback hinge for each of the impacts investigated (Figure 6). To reduce the T1 resultant acceleration, the optimized solutions for each impact severity increased the peak rotational velocity of the seatback and delayed it compared to the control condition. This finding agreed with previous computational studies that suggested decreased seatback hinge stiffness could reduce whiplash injury criteria (Choi & Bae, 2007; Shin et al., 2003). Similar to our study, Shin et al. (2003) found that hinge stiffness and maximum seatback rotation were the most important factors to reduce neck moments, and Choi et al. (2007) found that head restraint height and seatback hinge stiffness were the most important factors to reduce T1 acceleration.

The rebound velocity of the seatback was reduced to zero for each of the impacts investigated (Table 2). Reducing the rebound velocity is similar to fully plastic deformation of the seatback hinge in a conventional seat. Both conditions return no kinetic energy to the occupant after the seatback has deformed rearward. Reducing rebound energy is part of the design of the Volvo WHIPS seat, which uses the plastic deformation of a link in the seat hinge to absorb energy (Jakobsson, 2000). In this study, the rebound velocity was influential to the T1 resultant acceleration during the 16 km/h impact, but less so for the lower impact severities (Figure 6). Whether this result indicates that a WHIPS-like mechanism works better at higher collision severities requires additional work.

One limitation of this study is that some parameters ( $y_2$ ,  $x_2$  and  $y_3$ ) had optimized values at the variable limits (Tables 1 and 2). The  $x_2$  values were at their maximum values, which was set so that a smooth curve could be connected between the peak and final point on the seatback angular velocity curve. The  $y_3$  rebound velocity was at its lower limit, which was set so that the seatback was not still reclining at the end of the simulation. Finally, the peak angular velocity of the seatback was at its maximum, which was set to ensure the seatback stayed in contact with the back of the dummy. It is possible that further reductions of the T1 acceleration are possible by going beyond the current variable limits, and an exploration of these boundary values will be performed using the actual prototype seat and a biofidelic rear-impact dummy. Another limitation of the current study is the use of a Hybrid III dummy model instead of a dummy designed specifically for rear-impacts. Since the horizontal T1 acceleration of the HIII dummy closely matches that of human volunteers in rear-end crashes (Siegmund et al., 2001), we used this response variable rather than the less biofidelic head kinematics for our study.

## CONCLUSIONS

An actively controlled seatback can reduce peak neck kinematics by about 58 percent compared to a standard seatback, and could potentially reduce the risk of whiplash injury in rear-end collisions.

## ACKNOWLEDGEMENTS

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