# Evaluation of the Biofidelity of the BioRID-II and THOR-NT Anthropomorphic Test Devices under Seatbelt Pre-Pretensioner Loading in Stationary Conditions

J.-A. Develet[1], A. Carlsson[1], M. Svensson[1], R. Fredriksson[2], D. Bråse[2], S. Holcombe[3]
[1] Department of Applied Mechanics, Chalmers University of Technology, Sweden
[2] Autoliv Research, Sweden
[3] International Center for Automotive Medicine (ICAM), University of Michigan, USA

## ABSTRACT

*Pre-pretensioners are active and reversible devices that apply light tension to the seatbelt (less than 300N) which pulls road vehicle occupants rearwards and reduce the backset (head-to-head restraint horizontal distance). This action has been found to have the potential to reduce the number of whiplash injuries in rear impacts. However, pre-pretensioners induced a new load case on current Anthropomorphic Test Devices (ATDs) for which they have not been validated. The purpose of this study was to evaluate the biofidelity of two 50th percentile male ATDs (BioRID-II and THOR-NT), under pre-pretensioner loading in a stationary environment. A literature review resulted in three testing positions that either occur frequently (backset exceeding recommendations) or have high injury potential (leaning far forward at the driver and front passenger seats). Experiments comprised six volunteer subjects, the BioRID-II and the THOR-NT. Corridors for the head-neck complex kinematics, and interaction of the subjects with the seatbelt, were generated based on data from the volunteer tests and ATD responses were compared to the corridors in terms of amplitude, peak occurrence and shape. For slight out-of-position cases (backset ~80mm), the THOR-NT was found to be close to relaxed volunteers and the BioRID-II to tense volunteers; both were suitable for pre-pretensioner testing. Although the BioRID-II results were closer to the corridors than the THOR-NT results in the far forward leaning positions, neither showed sufficiently large rearward motions and head rotations to fit the corridors. Furthermore, head rotations were problematic for both ATDs in the three test positions. Therefore, construction changes to both the pelvis and occipital joints are suggested in order to improve the biofidelity of BioRID-II and THOR-NT in far forward leaning positions.*

## INTRODUCTION

The potential of pre-pretensioners – also known as pre-crash active seatbelts or motorized shoulder belts – in reducing severity of injury outcomes in different impact directions has been the focus of several studies (Kawaguchi 2003; Tobata 2003; Good 2008; Sander 2009; Mages 2011). These devices aim at improving the effectiveness of the seatbelt and head restraint (HR) which is affected by the occupant position (Stemper 2006; Sander 2009; Mages 2011). Out-of-position (OOP) describes the status of road vehicle occupants whose seated position does not correspond to the posture defined by official protocols. The present study focused on 1/frequent and 2/high injury potential mid-sagittal OOP issues. A frequent OOP case is drivers sitting too far from the HR; thus the backset exceeds the recommendations – below 70mm is rated “good” (RCAR-IIWPG 2008). Grounds for this backset limit lay in the high injury risk in rear-end impacts when backset is greater than 60mm (Jakobsson 2004; Stemper 2006). Male subjects were observed during car driving (motorway, urban context) in two studies; the first (35 males, average stature 181cm, SD 8cm) found an average backset of 77mm (Jonsson 2008) and the second (7 males, no stature recruitment criteria) of 85mm (Shugg 2011). In terms of frequency, the posture of drivers observed in 5,106 vehicles in different traffic contexts found backsets reported as "medium" – greater than 50mm – in 78% of cases (Bingley 2005). The second type focuses on high injury risk OOPs. Despite its rare occurrence (front passenger <5% (Zhang 2004), driver <11% (Bingley 2005), far forward leaning was found to pose great injury risk as occupants were far from the seatback and HR, and close to harmful surfaces (*e.g.* steering wheel) (Bose 2010). Pre-pretensioning pulls the occupants rearwards by tensioning the seatbelt with force levels of less than 300N (Lorenz 2001). By removing some belt slack and reducing the gap between occupant and seat before a collision, pre-pretensioners have the potential to improve the position of the occupant ahead of the collision and potentially contribute to reducing the severity of the injury outcome induced by OOP issues. This scenario introduces a new load case to current ATDs for which the biofidelity has not yet been evaluated. The purpose of the present study was to evaluate the biofidelity of two 50th percentile male ATDs (BioRID-II and THOR-NT), under pre-pretensioner loading in a stationary environment.

## METHODS

### Test scenarios

To date, an official protocol to assess the effectiveness of active restraints comprising OOP cases does not exist. Therefore, frequency and risk of several OOPs were reviewed and laid the foundations for the test scenarios implemented in the present study (Table1).

Table1: Test Matrix

| **Test ID** | **Position (Pos.)** | **Description** | **Backset [mm]** | **Nasion-Ref* [mm]** |
|---|---|---|---|---|
| 1 | Real life driving posture | • Driver seat<br>• Hands on the steering wheel<br>• Normal position according to "The dynamic assessment of car seats for neck injury protection testing protocol" (EuroNCAP 2011)<br>• Light forward (FW) leaning, backset representative to real life driving conditions (Jonsson 2008) | 80 | 425 |
| 2 | Attempting to increase visibility at intersections. | • Driver seat<br>• Hands on the steering wheel<br>• Far FW leaning, head in a position that replicates situations in which the driver attempts to increase visibility at an intersection. | 260 | 265 |
| 3 | Searching the glove box. | • Front passenger seat<br>• Hands on the lap<br>• Far FW leaning, head position replicating a situation in which the driver searches the glove box or the floor. | 400 | 265 |

** The reference (Ref) is a target on the steering wheel for Position1 and Position2 (driver seat) and a target on the dashboard for Position3 (front passenger seat).*

## Approach for evaluation of the biofidelity

*Response corridor approach.* The responses to pre-pretensioner loading of ATDs and volunteer subjects were compared in terms of amplitude, peak occurrence and shape using a response corridor approach. The latter corridors were generated from the volunteer subjects average response ±1 standard deviation (SD) based on the sample.

*Selection of parameters.* The evaluation of the biofidelity of the ATDs was based on kinematics of the head-neck complex as per the neck-link model (Wismans 1987) and the interaction of the subject with the seatbelt (Table2).

Table2: parameters for the evaluation of biofidelity

| Parameter | Definition | Motivation |
|---|---|---|
| Backset [mm]<br>Head-to-HR horizontal distance | • horizontal distance between the rearmost surface of the head and HR | • important parameter for the evaluation of neck injury risk (Farmer 1999; Stemper 2006; Jonsson 2008) |
| Travel of T1 [mm]<br>x-displacement of T1 | • distance travelled by the center of the body of T1 with regards to the x-axis of the test vehicle | • kinematics of the head is not directly coupled with the upper torso;<br>• describes the rearward motion of the upper torso |
| Rotation of the head [deg] | • change in angle of the head during its rotation around the y-axis,<br>• positive when the head leans downwards. | • the head – as per the neck link model – may show rotations around the occipital condyle. |
| Rotation of the neck [deg] | • change in angle of the head while rotating around the y-axis,<br>• positive when the neck flexes downwards. | • the neck – as per the neck link model – may show rotations around the center of the body of T1, the instantaneous axis of rotation (White 1978). |
| Seatbelt force [N]<br>tension force in the shoulder belt | • force in the belt between the shoulder and the D-ring | • cause of the motion,<br>• affected by the mechanical properties of the pelvic joints of the subject, e.g., muscle activity for volunteers, stiffness and dampening for ATDs. |

## Equipment, instrumentation and data processing

*Test environment.* Experiments were conducted in a passenger vehicle (VolvoXC70, model year 2009), selected for its similarity to the vehicle used in (Jonsson 2008) (Volvo V70, model year 2007). The test vehicle was stationary (parked) and the seats were set according to EuroNCAP testing protocol, with the steering wheel at mid-depth and mid-height and the D-ring at its highest setting. A prototype unit comprising two pre-pretensioners, power supply and controller was installed in the test vehicle. The Coordinate System was as per the standard J211 (SAE 2007).

*Instrumentation.* The pre-pretensioner and data acquisition system was implemented with a NI-USB6251 DAQ running two LabVIEW programs (National Instruments, USA);

one for analog channels, sampling at 2kHz, and one controlling a GigE UI-5220CP camera (IDS, Germany) equipped with a LM5NCL lens with a focal length of 4.5mm (Kowa, UK), sampling at 50Hz. The seatbelt force transducer (MESSRING, Germany) had a capacity of 2kN.

*Data processing.* Kinematics was tracked with TEMA3.5-012 (Image Systems, Sweden). The reference points and camera positions were measured with a FaroArm (FARO, USA). Compensation for distortion from the lens was applied; the resulting error was estimated to ±2mm (<1%) in the area of the head and upper body. The signal from the seatbelt force transducer was filtered with a Channel Frequency Class of 30 and the offset was corrected calculating the median over the 100 indices preceding the trigger. Analog data was synchronized at the start of the current supply (t=0) and kinematic data were linear-interpolated to match this event.

## Research Subjects

*ATDs.* As the pre-pretensioner load case is similar to a light frontal impact the THOR-NT was chosen; in addition pre-pretensioners have the potential of injury reduction in rear end impacts, hence the selection of the BioRID-II. Both ATDs were provided by Volvo Car Corporation.

*Human subjects.* Seven male subjects were selected based on the 50th percentile male anthropometric specifications (Schneider 1983) (Table3). They did not have a previous medical history of neck injury. The protocol of this study was reviewed and approved by the Ethical Review Board at the University of Gothenburg, Sweden.

Table3: Research subjects anthropometry

| Subject ID | Body weight [kg] | Seated height* [cm] | Stature [cm] | Age [year] |
|---|---|---|---|---|
| **BioRID-II** | 78 | 80 | 178 | N/A |
| **THOR-NT** | 78 | 79 | 180 | N/A |
| **Recruitment criteria** | 77±8 | N/A | 175±5 | 25±5 |
| **AM50.0** | 72 | 79 | 177 | 24 |
| **AM50.1** | 75 | 79 | 180 | 24 |
| **AM50.2** | 75 | 80 | 181 | 24 |
| **AM50.3** | 70 | 76 | 175 | 25 |
| **AM50.4** | 72 | 77 | 175 | 24 |
| **AM50.5** | 76 | 80 | 180 | 25 |
| **AM50.6** | 76 | 77 | 175 | 25 |
| **AM50.7** | 70 | 77 | 180 | 24 |
| **Average** | 73 | 78 | 178 | 24 |
| **Standard Deviation** | 3 | 2 | 3 | 1 |

**Distance between the trochanter major and the top of the head in a posture close to (EuroNCAP 2011) protocols; measured on research subjects inside the test vehicle, precision ±2cm.*

*Film targets.* Two skin landmarks were positioned on the subjects, one in line with the proximal ends of the clavicles and one in line with the spinous process of T1 (Figure1). CT scan data extracted from the University of Michigan morphomics database (Parenteau 2013), allowed for locating the center of the body of T1 based on the position of the skin landmarks.

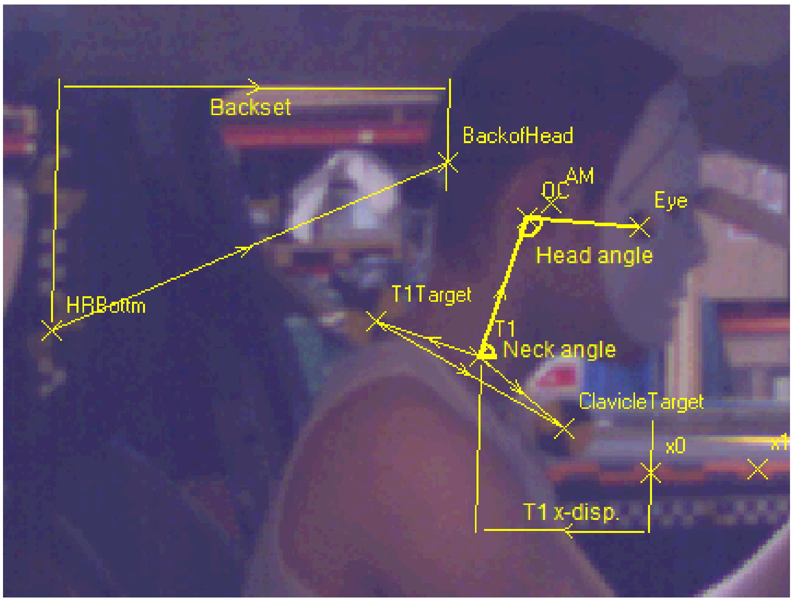

Figure1: location of skin landmarks and the center of the body of T1 on a volunteer subject. Adapted from a screenshot from TEMA3.5-012. Cropped frame, color correction.

*Experimental precautions.* Support rods were used to position the volunteer subjects in a repeatable manner. ATDs and volunteer subjects wore cotton T-shirts from the same batch to ensure similar friction with the seatbelt. Before activating the pre-pretensioner, the seatbelt was unbuckled and the webbing was pushed in and pulled out to avoid tightening effects around the spool. The test leader perceived the behavior of the volunteer subjects to be either “tense” or “relaxed”.

## RESULTS

### Seatbelt force

*Seatbelt force characteristics.* The seatbelt characteristics presented three phases (Figure3). In the first phase, the seatbelt force continuously increased as the webbing was retracted and the belt slack reduced, until the first peak was reached at ~0.25s (Table2). In the second phase, subjects started to move rearwards, relative to the seatback, resulting in a temporary reduction of the seatbelt force. However, as the rearward motion was stopped by the seatback, the seatbelt force increased again, reaching a second peak at ~0.5s (Table3). The third phase started after the second peak. The power supply to the pre-pretensioner ended, resulting in a drop in the force level and the pre-pretensioner maintained approximately the same force level. In addition, for extreme positions (2 and 3), a third peak corresponding to a damped oscillation in the seatbelt force at ~0.6s was observed as the subjects displayed a minor rebound (Table4).

Table4: Occurrence and seatbelt force levels for the first peak

| | **Peak occurrence [s]** | | | **Force level [N]** | | | **Gradient of slope [kN/s]** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **Pos.1** | **Pos.2** | **Pos.3** | **Pos.1** | **Pos.2** | **Pos.3** | **Pos.1** | **Pos.2** | **Pos.3** |
| BioRID | 0.20 | 0.25 | 0.20 | 265 | 265 | 140 | 1.8 | 0.9 | 0.9 |
| THOR | 0.20 | 0.25 | 0.20 | 210 | 210 | 175 | 1.4 | 0.6 | 1.2 |
| Vol. subj. mean | 0.30 | 0.20 | 0.20 | 245 | 245 | 110 | 1.0 | 0.9 | 0.7 |

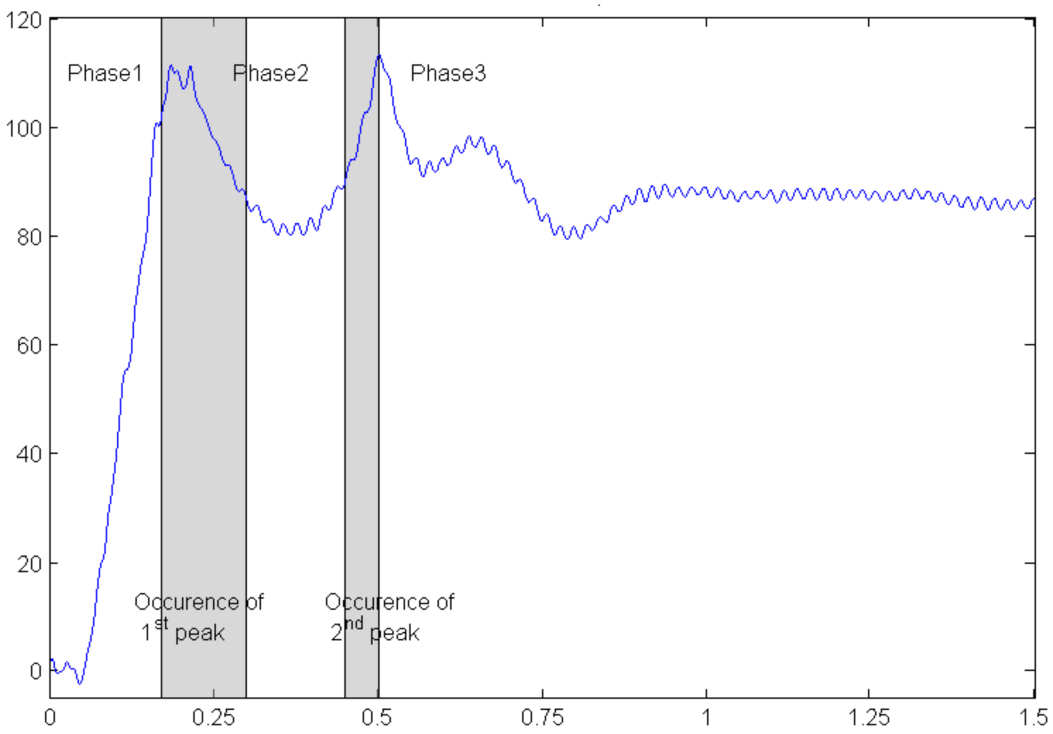

Figure2: seatbelt force phases. Seatbelt force in N *vs.* time in s.

Table5: Occurrence and seatbelt force levels for the second peak

| **Subject** | **Peak occurrence [s]** | | | **Force level [N]** | | |
|---|---|---|---|---|---|---|
| | **Pos.1** | **Pos.2** | **Pos.3** | **Pos.1** | **Pos.2** | **Pos.3** |
| BioRID-II | 0.50 | 0.45* | 0.50 | 250 | 160 | 130 |
| THOR-NT | 0.50 | 0.50 | 0.50 | 220 | 120 | 165 |
| Vol. subj. mean | 0.50 | 0.50 | 0.50 | 250 | 200 | 110 |

** Minor power supply issue*

Table6: Occurrence and seatbelt force levels for the third peak (first rise)

| **Subject** | **Peak occurrence [s]** | | **Force level [N]** | |
|---|---|---|---|---|
| | **Pos.2** | **Pos.3** | **Pos.2** | **Pos.3** |
| BioRID-II | 0.60 | 0.75 | 110 | 150 |
| THOR-NT | 0.70 | 0.75 | 95 | 145 |
| Vol. subj. mean | 0.60 | 0.65* | 180 | 100* |

** In the area of large standard deviation for the corridor.*

*Comparisons of ATDs and volunteer subjects in terms of seatbelt force characteristics (AppendicesA-C).* For Position1 and Position3, the THOR-NT and the BioRID-II showed quicker seatbelt force responses than the volunteers as the initial slope was steeper and the first peak occurred earlier (0.20s compared to 0.30s, Table4). For Position1, the force peaks of the BioRID-II were close to the mean response of the volunteer subjects, while for the THOR-NT they were close to the inferior boundary of the corridor (AppendixA2). For the BioRID-II, the asymptote exceeded the mean force by 40N at t=1.5s. At the same time, the force almost reached the mean (10N less) for THOR-NT. The force levels of both ATDs were comparable to those of the volunteer subjects for Position1. In Position3, both ATDs were close to the upper boundary of the corridor (AppendixC2). The peaks occurred synchronously for the ATDs and the volunteers mean response, although both ATDs showed greater first peaks than the volunteers (THOR-NT 175N, BioRID-II 140N, volunteer subjects mean 110N, Table4). Consequently, the ATDs had a greater amplitude of oscillation after t=0.5s (100N) than the volunteer subject mean (<30N). Overall, the BioRID-II appeared to be closer to the force corridor than the THOR-NT for Position3. In Position2 (AppendixB2), the force response of the ATDs was delayed by ~0.05s compared to the volunteer subjects mean (Table5). In terms of slope and force levels of the two first peaks, the BioRID-II (respectively 0.9kN/s, 265N and 160N, Tables4-5) was closer to the volunteer subjects mean (0.9kN/s, 245N, 200N) than the THOR-NT (0.6kN/s, 210N, 120N).

## Kinematics

*Backset and T1 x-displacement.* In Position1, the backset and T1 x-displacement of the ATDs were faster than the volunteer subjects mean (by 0.20s and 0.05s, respectively, Tables7-8, AppendixA2). The backset of the ATDs had greater amplitudes (BioRID-II 35mm, THOR-NT 53mm) than the volunteer subjects mean (28mm). However, neither the THOR-NT nor the BioRID-II were in contact with the HR for Position1 (Table10). Furthermore, for Position1, the THOR-NT had a greater T1 x-displacement than the BioRID-II and was slightly closer to the volunteer subjects mean than the BioRID. In Position2, even though the initial backsets of the BioRID-II (~40mm) and THOR-NT (~70mm) were greater than the volunteer subjects mean (Table10, AppendixB2), the amplitude and peak occurrence of backset were closer to the volunteer subjects for BioRID-II than for THOR-NT. However, accounting for the difference in initial backset would lead to an asymptote in backset of ~70mm for the BioRID-II and ~80mm for the THOR; these were twice as large as the volunteer subject mean. In addition T1 x-displacement recorded for the BioRID-II (110mm) and the THOR-NT (105mm) were quite different (smaller by more than 33%) from the volunteer subjects mean (180mm) (Tables7-8). In terms of shape, despite the larger overrun in backset and T1 x-displacement at ~0.60s for the BioRID-II compared to the THOR, the BioRID-II was closer to the volunteer subjects mean for the backset and T1 x-displacement. None of the ATDs had contact with the HR (Table10). Results for Position3 and Position2 were similar.

Table7: Amplitude, peak occurrence and asymptote of the backset

| | **Amplitude [mm]** | | | **Peak occurrence [s]** | | | **Asymptote [mm]** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **Pos.1** | **Pos.2** | **Pos.3** | **Pos.1** | **Pos.2** | **Pos.3** | **Pos.1** | **Pos.2** | **Pos.3** |
| BioRID-II | 35 | 222 | 316 | 0.40 | 0.55 | 0.70 | 52 | 101 | 179 |
| THOR-NT | 53 | 179 | 196 | 0.40 | 0.60 | 0.60 | 20 | 147 | 241 |
| Vol. subj. mean | 28 | 231 | 354* | 0.60 | 0.55 | 0.60* | 41 | 31 | 62 |

Table8: Amplitude, peak occurrence and asymptote of T1 x-displacement

| | **Amplitude [mm]** | | | **Peak occurrence [s]** | | | **Asymptote [mm]** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Subject** | **Pos.1** | **Pos.2** | **Pos.3** | **Pos.1** | **Pos.2** | **Pos.3** | **Pos.1** | **Pos.2** | **Pos.3** |
| BioRID-II | 23 | 120 | 210 | 0.40 | 0.50 | 0.65 | 20 | 110 | 180 |
| THOR-NT | 36 | 110 | 130 | 0.40 | 0.60 | 0.6 | 36 | 105 | 120 |
| Vol. subj. mean | 31 | 180 | 250* | 0.45 | 0.55 | 0.6* | 28 | 180 | 260 |

** Large spread in volunteer response; for comparison purposes, the peak is interpreted around t=0.6s (following the lower boundary of the corridor)*

*Head-neck complex.* The amplitudes of the neck and head rotations were equal or less for the THOR-NT than for the BioRID-II in all three positions (Table9). Furthermore, the peak head rotations of the ATDs were less than those of the volunteer subjects mean in all positions. However, the peak neck rotation was greater for the BioRID-II than for the volunteer subjects for Position2 and Postition3. For the ATDs, only positive rotations were recorded, while the volunteer subjects posed an additional negative peak in the initial phase. In fact, the ATDs only displayed extension motions, while the volunteer subjects experienced a dual motion – the initial flexion of the head-neck complex was followed by an extension.

Table9: Amplitude (max - min) of head and neck rotations.

| **Subject** | **Head rotation [deg]** | | | **Neck rotation [deg]** | | |
|---|---|---|---|---|---|---|
| | **Pos.1** | **Pos.2** | **Pos.3** | **Pos.1** | **Pos.2** | **Pos.3** |
| BioRID-II | 2 | 6 | 7 | 5 | 35 | 48 |
| THOR-NT | <1 | <1 | 2 | 5 | 17 | 21 |
| Vol. subj. mean | 5 | 10 | 15 | 7 | 30 | 38 |

## DISCUSSION

*Computation of the corridors.* Standard deviations and means were not strongly significant as the number of volunteer subjects per test position was only six. The time to return occupants to the seat and the effect of individual behavior on the response became greater when the degree of forward leaning was increased. On the one hand, the dataset was comprised of different potential reactions in real life, but on the other hand, the width of the corridors increased. For Position3, the corridor was wide in Phase3, reaching approximately 140N, in comparison to the mean (around 90N, AppendixC1).

*Effect of individual behavior on volunteer responses.* While tense subjects mainly showed a single downward motion, relaxed subjects displayed both flexion and extension kinematics (Appendices, Table10). Tense subjects may have contracted different muscle groups along the upper body and head-neck complex, which limited their range of motion; AM50.2 and AM50.3 depicted this phenomenon in Position1, presenting lower amplitudes than relaxed subjects (AM50.0, AM50.5). Besides, individual behavior altered the head-neck motion, see AM50.3 who protracted while others flexed. In fact, his head went moved forward (+15mm), producing the opposite effect of what was expected - moving both the head and torso backwards. Relaxed subjects may have aided and emphasized the response of the pre-pretensioner as seen in AM50.0 whose peak seatbelt force oscillated in the beginning (peaks at 0.12s and 0.24s, AppendixA1), as if he was waiting for the trigger and reacting accordingly. This would provide grounds for the delay of 0.2s in his kinematics, as compared to AM50.5 who was also relaxed. Besides, in Position2, AM50.2 appeared to activate certain neck muscles on return; the amplitude of his head and neck rotations were 40deg (mean curve 11deg) and 55deg (30deg), respectively.

*Comparison of ATD and volunteer response in terms of behavior*. For Position1, THOR-NT resembled relaxed volunteer subjects, and the BioRID-II tense subjects, in terms of seatbelt force, backset and T1 x-displacement (AppendixA2, Table9). However, head and neck rotations of the ATDs were too different from those of the volunteer subjects in amplitude, shape and delay, to draw conclusions. For Position2, both ATDs showed deficiencies in reproducing T1 x-displacements by travelling less than the volunteer subjects at ~50mm and ~70mm, respectively (Tables7-8, AppendicesB2-C2). All responses of the

BioRID-II, bar neck rotation, fitted better or were closer to the corridors than the THOR-NT. In fact, neck rotation of the BioRID-II was too large. Results for Position3 were similar to Position2.

Table10: spread in initial seated postures (backset), contact with the HR, overall behavior impression from the test leader

| **Subject** | **Pos.1** | | | **Pos.2** | | | **Pos.3** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Backset** | **HR contact** | **Overall behavior** | **Backset** | **HR contact** | **Overall behavior** | **Backset** | **HR contact** | **Overall behavior** |
| AM50.0 | 82 | 1 | Relaxed. Helping? | 258 | 1 | Relaxed. Helping? | *test not valid* | | |
| AM50.1 | 76 | 0 | Relaxed++ | 251 | 1 | Relaxed++ | 392 | 0 | Relaxed |
| AM50.2 | 71 | 0 | Tense slight protraction? | 270 | 1 | Tense Self-muscle activation? | 49 | 1 | Relaxed Self-muscle activation? |
| AM50.3 | 74 | 0 | Tense Head moved forward | 235 | 0 | Relaxed | 393 | 0 | Relaxed Freezes after contact with seat |
| AM50.4 | *test not valid* | | | *test not valid* | | | 379 | 1 | Relaxed |
| AM50.5 | 76 | 1 | Relaxed. Helping? | 235 | 1 | Helping? | 391 | 1 | Relaxed Freezes after contact with seat |
| AM50.6 | 70 | 0 | Tense | 231 | 0 | Tense | *test not valid* | | |
| AM50.7 | *test not valid* | | | *test not valid* | | | 384 | 0 | Relaxed Particularly slow |
| Average | 75 | | | 248 | | | 391 | | |
| SD | 4 | | | 14 | | | 10 | | |
| BioRID-II | 76 | 0 | | 293 | 0 | | 437 | 0 | |
| THOR-NT | 70 | 0 | | 318 | 0 | | 422* | 0 | |

** THOR-NT without jacket on Test3*

*Effect of the support rod on the seated posture.* Different combinations of head and neck angles allowed for holding the support rod still. There might be effects on the kinematics, as the initial posture affected the position of the head and thus the initial backset (Figure3). This would explain the SD in backset (Table10). However, no major effect of the initial posture on the volunteers' response was observed.

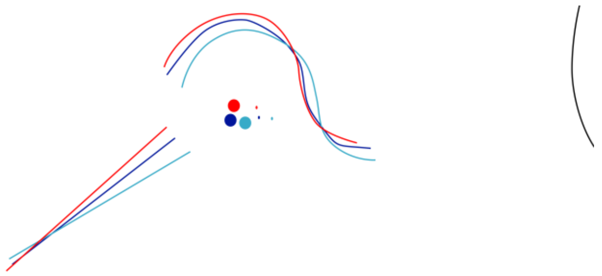

Figure3: Different initial seated postures for three volunteers in Position 3. The contours of the head and HR were in the mid-sagittal plane. The straight line is the support rod, the large dot the target at the *Auditori Meatus*, and the small dot the *Occipital Condyle*. The color scheme follows the plots of the volunteer subjects (AppendixC1).

*ATD seated position and OOP instability.* Both ATDs had difficulties holding the predefined posture in Position2 and Position3, and had a tendency to return to the seat. This effect was greater for Position2 than Position3. In order to avoid the retractor pulling the ATDs and increasing the instability, some belt slack was set between the shoulder and the D-ring. This was not the case for the volunteers who tensioned the seatbelt while leaning forward. This may explain the time delay of 0.05s (Table4) at the beginning of Position2 in the ATDs seatbelt force and lower force level with regards to the corridor in Position2 as compared to Position1 and Position3.

*Minor issue with the power supply.* Due to the state of the battery an early drop in the seatbelt force was observed in Position2 with BioRID-II (Table5). The amplitude of the damped oscillation in Phase3 and the asymptote level at t=1.5s may have been affected. However, this advance (0.05s) was rather insignificant and any impact on the kinematics should be limited.

*THOR-NT, construction detail.* The instrumentation wires that of the ATD utilized for the tests exited the body in the region of the lumbar spine; they may have potentially interacted with the seat.

*Tentative improvement suggestions to the construction of the ATDs.* Both ATDs had difficulties reproducing the head rotation, which points towards a modification of the occipital joint. In addition, modifications to the neck may help reproducing the initial flexion. For far forward leaning positions, both ATDs posed too low T1 x-displacement and improvements to the pelvis joint would also be necessary.

## CONCLUSIONS

Over the three tests, BioRID-II was found to reproduce the volunteer subjects mean response more appropriately than THOR-NT. Both ATDs showed limitations with regards to the reproduction of the dual extension-flexion motion, head rotation and upper torso x-displacement of the volunteers. BioRID-II was closer to the tense subjects and THOR-NT to relaxed subjects for light OOP cases. Construction changes to the pelvis and occipital joints may lead to improvements in the biofidelity of these ATDs under pre-pretensioner loading. The latter loading reduced the degree of OOP towards more tolerable levels of backsets which shows the potential of this type of active restraint in injury prevention for 50th percentile male subjects, in the driver and front passenger seat, in rear-end collisions. The evaluation of the biofidelity of other size groups and gender, including tests in the rear seat, would actively contribute to the development and implementation of pre-pretensioners in road vehicles of tomorrow.

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# REFERENCES

Bingley, L., Morris, R. and Cross, G. (2005). Determination of real world occupants postures by photo studies to aid smart restraints development. 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Windsor, Ontario, Canada.

Bose, D. C., J. R.; Untaroiu, C. D.; Maslen, E. H. (2010). "Influence of pre-collision occupant parameters on injury outcome in a frontal collision." Accident Analysis & Prevention 42(4): 1398-1407.

EuroNCAP (2011). EuroNCAP - The dynamic assessment of car seats for neck injury protection testing protocol. www.euroncap.com.

Farmer, C. M., Wells, J. K. and Werner, J. V. (1999). "Relationship of head restraint positioning to driver neck injury in rear-end crashes." Accident Analysis & Prevention 31(6): 719-728.

Good, C. A., Viano, D. C., McPhee, J. J., Ronsky, J. L. and Pieper, J. K. (2008). Motorized Shoulder Belt Tensioning: Modeling and Performance for a Diverse Occupant Population, SAE International.

Jakobsson, L. (2004). "Field Analysis of AIS1 Neck Injuries in Rear-End Car Impacts - Injury Reducing Effect of the WHIPS Seat." Journal of Whiplash & Related Disorders 3(2): 37-53.

Jonsson, B., Stenlund, H. and Björnstig, U. (2008). "Backset—Stationary and During Car Driving." Traffic Injury Prevention 9(6): 568-573.

Jonsson, B. S., Mats; Linder, Astrid; Björnstig, Ulf (2008). "BioRID II manikin and human seating position in relation to car head restraint." International Journal of Crashworthiness 13(5): 479-485.

Kawaguchi, K., Kaneko, N., Iwamoto, T., Fukushima, M., Abe, A. and Ogawa, S. (2003). Optimized Restraint Systems for Various-Sized Rear Seat Occupants in Frontal Crash, SAE International.

Lorenz, B. K., D.; Strohbeck-kuehner, P.; Mattern, R.; Class, U.; Lueders, M. (2001). "Volunteer tests on human tolerance levels of pretension for reversible seatbelt tensioners in the pre-crash-phase. Phase i results: tests using a stationary vehicle." Proceedings of the International Research Council on the Biomechanics of Injury Conference 2001: 311-322.

Mages, M., Seyffert, M. and Class, U. (2011). "Analysis of the pre-crash benefit of reversible belt pre-pretensioning in different accident scenarios." Proceedings: International Technical Conference on the Enhanced Safety of Vehicles 2011.

Parenteau, C., Holcombe, S., Zhang, P., Kohoyda-Inglis, C. and Wang, S. (2013). The Effect of Age on Fat and Bone Properties along the Vertebral Spine, SAE International.

RCAR-IIWPG (2008). Seat/Head Restraint Evaluation Protocol (Version3) Measurement and Rating of Static Head Restraint Geometry – The Initial Evaluation http://www.iihs.org/.

SAE (2007). Instrumentation for Impact Test. S. T. I. S. Comm, SAE. J211.

Sander, U., Mróz, K., Boström, O. and Fredriksson, R. (2009). "The Effect of Pre-Pretensioning in Multiple Impact Crashes." Proceedings: International Technical Conference on the Enhanced Safety of Vehicles 2009: -.

Schneider, L. W., Robbins, D. H., Pflüg, M. A. and Snyder, R. G. (1983). Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family, Final Report. Ann Arbor, Michigan, USA, University of Michigan Transportation Research Institute.

Shugg, J. A. J., Vernest, K. and Dickey, J. (2011). "Head Restraint Backset During Routine Automobile Driving: Drivers Usually Exceed the Recommended Guidelines." Traffic Injury Prevention 12(2): 180-186.

Stemper, B. D., Yoganandan, N. and Pintar, F. A. (2006). "Effect of head restraint backset on head–neck kinematics in whiplash." Accident Analysis & Prevention 38(2): 317-323.

Tobata, H., Takagi, H., Pal, C. and Fukuda, S. (2003). Development of Pre-Crash Active Seatbelt System for Real-World Safety. Nagoya (Japan), Proceedings 18th ESV Conference.

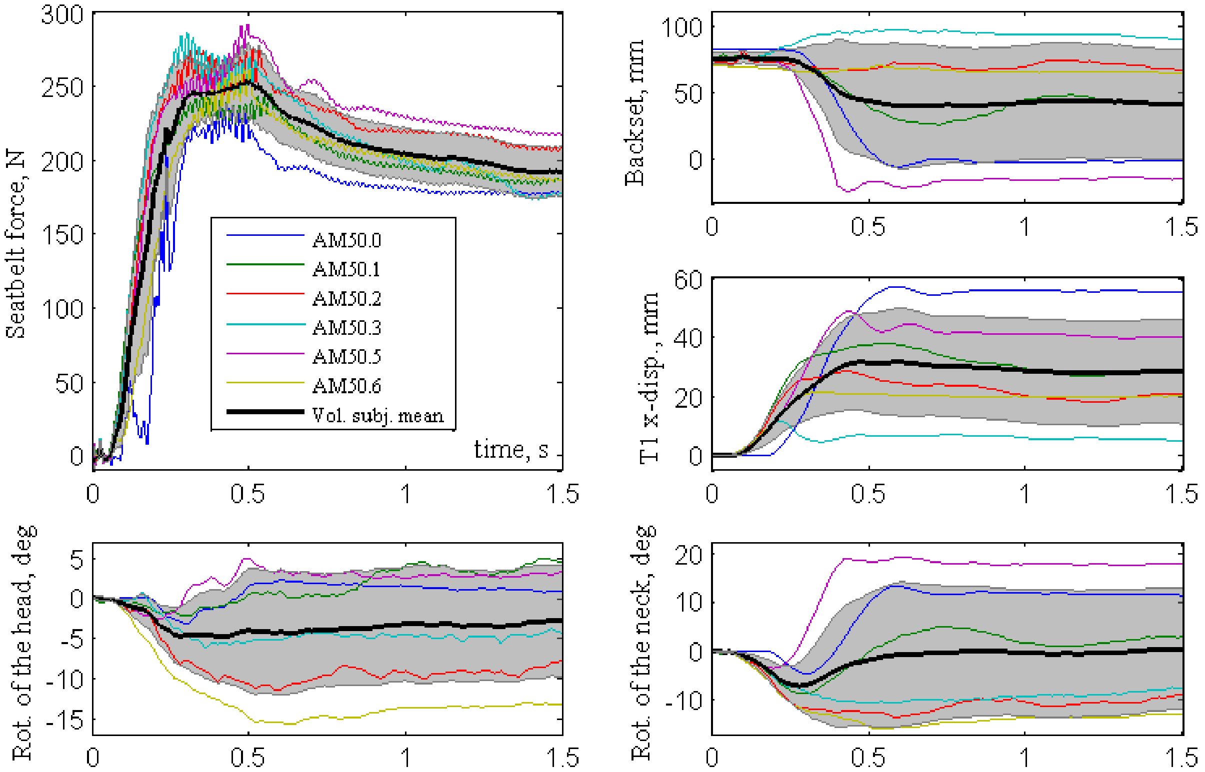
White, A. A. and Panjabi, M. M. (1978). Clinical biomechanics of the spine, Lippincott.

Wismans, J., Philippens, M., Oorschot, E. v., Kallieris, D. and Mattern, R. (1987). Comparison of Human Volunteer and Cadaver Head-Neck Response in Frontal Flexion, SAE International.

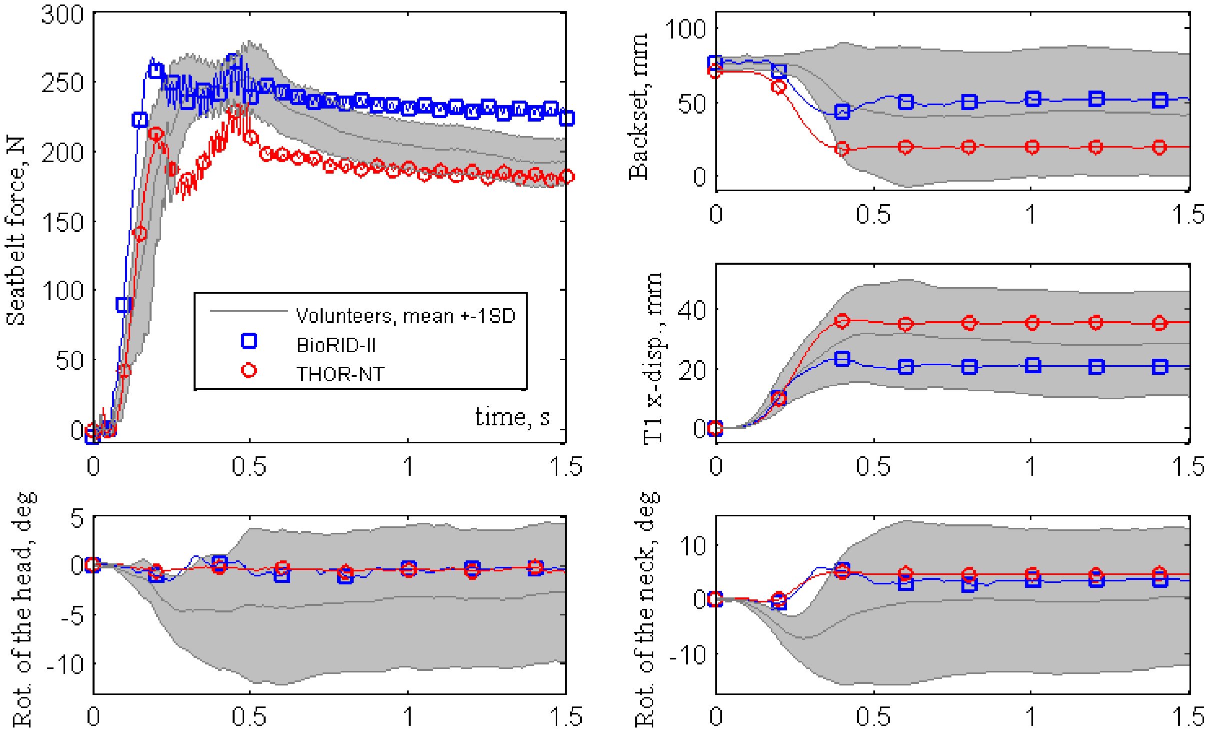
Zhang, L., Chen, L., Vertiz, A. and Balci, R. (2004). Survey of Front Passenger Posture Usage in Passenger Vehicles, SAE International.

## APPENDIX A – Volunteer subjects responses, corridors, ATDs responses for Position1 (backset exceeding recommendations, ~80mm)

### AppendixA1: volunteer subjects data and corridors for Position1. N=6.

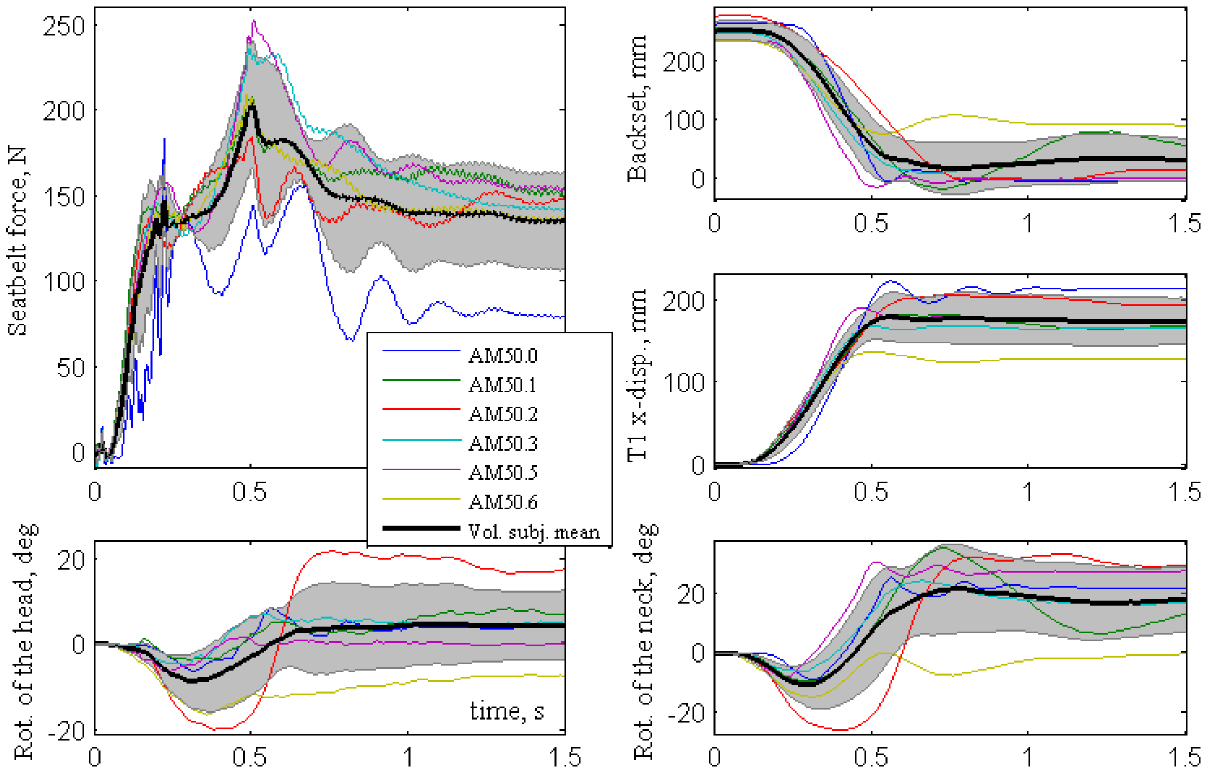


### AppendixA2: BioRID-II and THOR-NT responses *vs.* corridors, Position1.

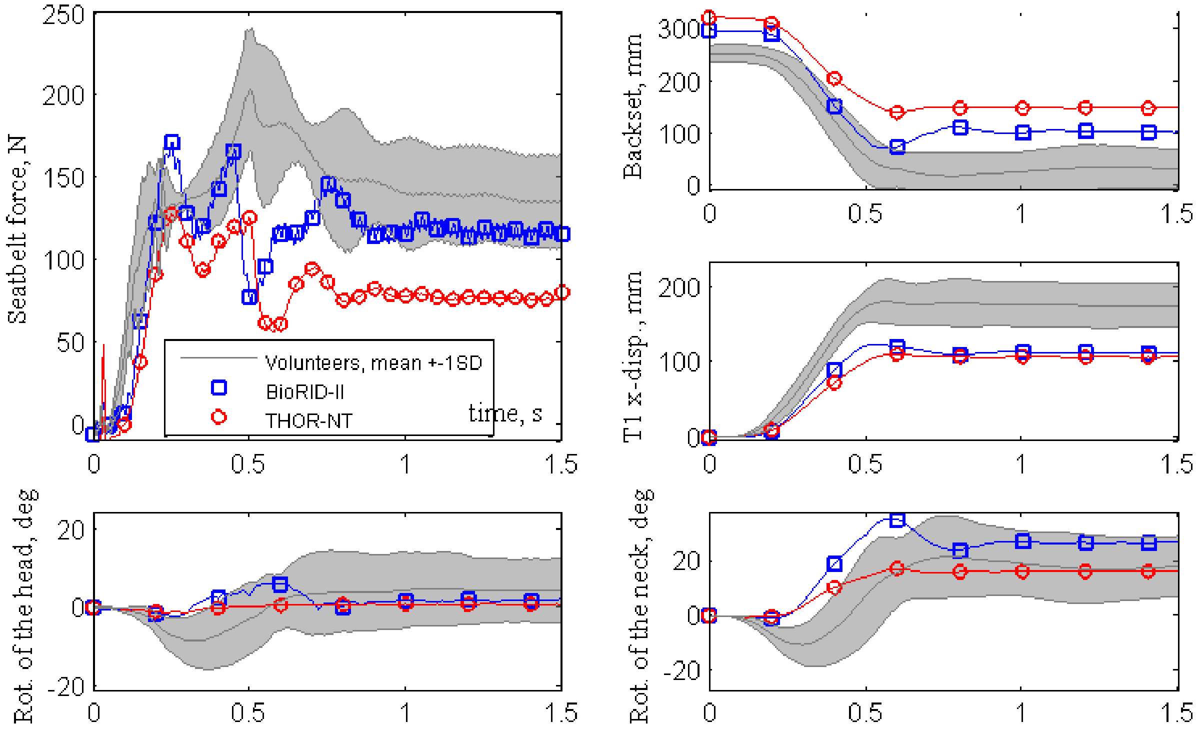


# APPENDIX B – Volunteer subjects responses, corridors, ATDs responses for Position2 (driver leaning far forward, ~260mm)

## AppendixB1: volunteer subjects data and corridors for Position2. N=6.

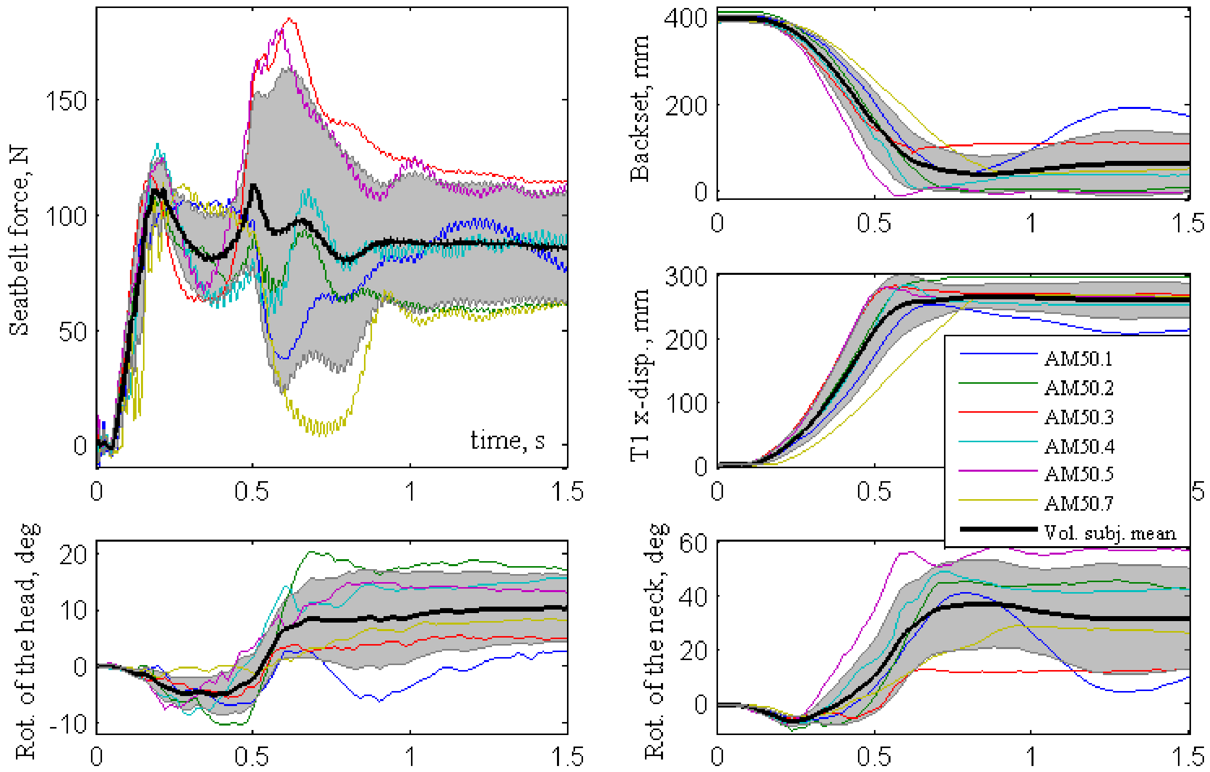


## AppendixB2: BioRID-II and THOR-NT responses *vs.* corridors, Position2.



# APPENDIX C – Volunteer subjects responses, corridors, ATDs responses for Position3 (front passenger leaning far forward, ~400mm)

## AppendixC1: volunteer subjects data and corridors for Position3. N=6.



## AppendixC2: BioRID-II and THOR-NT responses *vs.* corridors, Position3.