# INTEGRATED SAFETY FOR OCCUPANT PROTECTION

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## ABSTRACT

Integrated vehicle safety aims to connect active and passive safety technologies and has the potential to go far beyond what each can achieve separately. Improving integrated vehicle safety has become highly relevant for the development of automated vehicles.

The goal of the ISOP project is to investigate whether applying active safety features and manoeuvres during the pre-crash phase can negatively influence the performance of the vehicles’ restraint systems in a way that the state-of-art passive safety systems are no longer as effective in preventing fatalities and avoiding or mitigating injuries in road accidents.

A couple of test protocols have been defined within the project to analyse the effects of pre-crash manoeuvres on the initial occupant posture. The data from the tests with volunteers in proving ground performing cut-out manoeuvres have been collected and have been used as input database for the simulations with the Human Body Models (HBM). Due to the limitations of the Anthropometric Test Devices (ATD) in responding to a pre-crash manoeuvre, the effectiveness and sensibility of the restraint systems has been evaluated by HBM.

In contrast to ATDs, virtual Human Body Models (HBM) represent the anatomic structure of human beings including bones, flesh, skin, fat, and soft tissue. The high model detail allows a direct assessment of the injury risk based on the damage applied to the respective body region (e.g., in form of stress or strain), assuming a correct damage prediction of the model.

Integrated safety enhances comfort, convenience and can help assist in critical driving situations and in protecting occupants. However, the state-of-the art restraint systems need to be evaluated in such novel load cases including the activation of vehicle active safety systems and the pre-crash manoeuvres.

This paper focuses on the influence of active safety systems towards the protection of vehicle occupants in the event of a crash that has not been avoided, by developing a combined series of test protocols, performing volunteer tests and HBM simulations.

## INTRODUCTION

One of the main objectives of vehicle safety engineers is to protect occupants when there is a risk of crash event, either by means of pre-crash safety systems or by means of in-crash performance of the restraint systems and vehicle structure once the crash is unavoidable. The motivation of the ISOP project, and of this paper, is the study how the pre-crash safety manoeuvres affect the position of the occupant in the initial phases of the crash and; therefore, influence the effectiveness of the state-of-the-art restraint systems.

Anticipation and a braced response can change the kinematics of the vehicle’s passenger and have an effect on the outcome of the injury mechanism [1]. At T0, moment of the crash, not only the change of position is of importance but also the muscular activity. Occupants’ response to the threat, plays an important role in the final performance of the restraint systems and consequently the injuries provoked by the accident.

To study the pre- and in- crash phase, Anthropometric test devices (ATDs) and Human Body Models (HBMs) have been evaluated. ATDs used in occupant safety testing represent a limited application regarding the pre-crash active responses of the occupant to the upcoming impact scenario. The main application of these devices is in medium- to high-severity impacts and the negative aspect of them is that they are only passive and mechanically stiff compared to other technologies. To evaluate the pre-crash response properly and to be able to mimic the response of volunteer testing, virtual testing using HBMs has been considered to be the correct approach for this study.

Four available human body models were evaluated and compared based on the different characteristics that each one had. The four models chosen were the THUMS (Total HUman Model for Safety) from Toyota, the active HBM from Simcenter Madymo, the ViVA human body model (Virtual Vehicle-safety Assessment), and the Active HBM from SAFER.

The vehicle model which will be used in the next phase of the ISOP study will be the CUPRA Formentor FE model. THUMS and ViVA models were selected as main models to be used in the next phase of the project. This decision was given by analysing the variables included in the HBM comparison study that was conducted in parallel to ISOP by means of an internal project in IDIADA (HBM_in_AV) (see Table 1).

*Table 1*
*HBM Comparison for ISOP study*

| | **THUMS** | **MADYMO** | **ViVA** | **SAFER** |
|---|---|---|---|---|
| **Active/Passive model** | Active/Passive | Active/Passive | Passive | Active/Passive |
| **Available body sizes (percentiles)** | 5th, 50th, and 95th | 5th, 50th, and 95th and children | Female 50th | 50th percentile only. Female 50th in the process |
| **License** | Open Source | Tokens | Open Source | Need to be a partner of the SAFER investigation group |
| **Partner that uses it** | TOYOTA, general use | Siemens, general use | Volvo Cars, The Swedish National Road and Transport Research Institute (VTI) | Volvo, SAFER, Autoliv |
| **Software** | LSDYNA | MADYMO | LSDYNA | LSDYNA |
| **Positioning tool** | Not a specific one. Need to perform a simulation for adjusting the posture of the model | Manual definition of the initial angles of the joints | Not a specific one. Need to perform a simulation for adjusting the posture of the model | Not a specific one. Need to perform a simulation for adjusting the posture of the model. NEW TOOL INCOMING |
| **Injury reports** | Bone fracture, ligament rupture, brain injury, and internal organ injury | Injury criteria related to accelerations and forces | Not sure | Rib cage fracture model, Brain strain model, Spine model. Not sure if it has ligament or muscle rupture predictors. |
| **Validation** | Reports with PMHS for both the mechanical model and the active muscle model, not real motion with volunteers | PMHS | Female PMHS tests | Validation with real volunteers was developed. Originally based on THUMS. |

In order to be able to study the load cases with the selected HBMs, the testing subjects were selected by the specific anthropometry criteria which represents a 50th -percentile male THUMS HBM and 50th -percentile female ViVA HBM as follows:

- 50% male THUMS HBM = height: 178.6 cm and weight=78.5 kg
- 50% female VIVA HBM = height: 161.6 cm and weight=62.7 kg

To be able to identify the most relevant and most frequently occurring accidents and to still focus on the standardised protocols, an accidentology study and a review of the Euro NCAP protocols has been performed. From the created database [3], [4], two load cases have been studied (Figure 1):

- Urban Rear-end: Target vehicle braking in front of the following EGO (vehicle to be affected, studied) vehicle on a straight road.
- Urban Crossing: Target vehicle crossing in front of EGO vehicle at a junction from the right side.

*Figure 1: Load cases: rear-end (left; EGO vehicle - black) and crossing (right; EGO vehicle - black)*

The ISOP project is focused on a combination of all of the above-mentioned aspects with the goal of understanding the influence of the occupant's repositioning and muscle activation response on the safety of today's vehicles by means of a series of volunteer tests which will be compared with THUMS and ViVA human body models in the next project phase.

## METHODOLOGY

### Safety feasibility study

To analyse the safety conditions of the testing environment, a simulation-based feasibility study was completed. The first part of the study consisted of the definition of the braking manoeuvre deceleration pulse. It was estimated that a current modern car can generate a maximum sustained braking force of around 1g [9.8 m/s2]. Some even more advanced models can reach 1.1g by helping the occupant to brake by increasing the hydraulic braking pressure when a hard braking manoeuvre is detected. For simplification and to ensure the repeatability of the tests, the maximum deceleration for this analysis was set at 1g. In addition, the deceleration jerk or brake gradient was set at 66 m/s3 representing the average deceleration jerk for a generic AEB pulse. The resulting pulse is shown on Figure 2.

For simulation purposes, pre-crash manoeuvres are defined in negative time as the theoretical crash is defined to start at time 0. The test is estimated to be performed at around 70 km/h. If a car applies the mentioned deceleration pulse at that velocity, the evolution of the velocity can be seen on Figure 3.

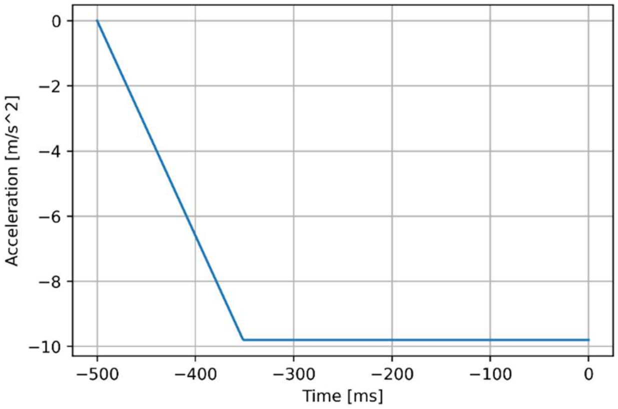


*Figure 2: Deceleration pulse*

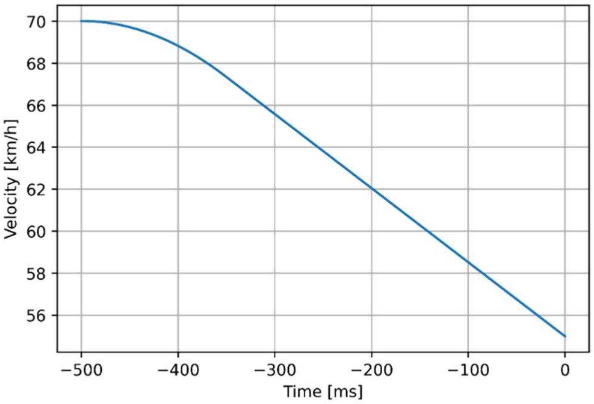


*Figure 3: Braking velocity from 70km/h*

To simulate the full 3-second pre-crash manoeuvre without using excessive computational resources, a Madymo model was used. [2] Madymo is a multibody-based simulation software designed for developing crash simulation analysis. The software also counts with HBMs with active musculature that make it possible to recreate real human behaviour during a pre-crash or in-crash phase using less computational time than a finite element solver like LS-Dyna. The model used for this study was developed in the OSCCAR project in which a generic car environment was developed [2].

The HBM was placed on the passenger side to recreate the volunteer tests and the deceleration pulse was applied to study the displacement of the body of the model and the possible injuries that could be produced due to the braking manoeuvre. In these conditions, the maximum head displacement was 16.5 cm forward and it occurred at -2.28s. The maximum knee forward displacement was 2cm and occurred at -2.61s.

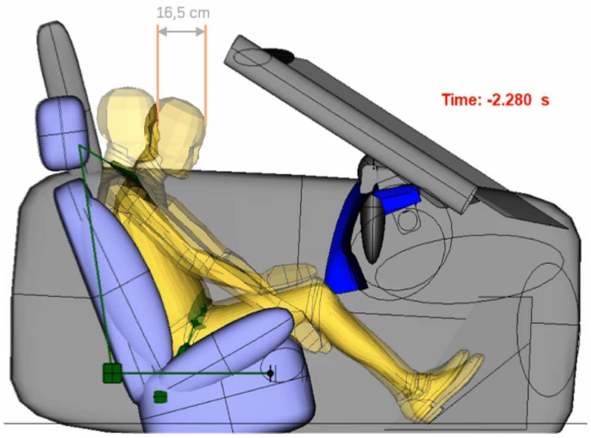


*Figure 4: Madymo feasibility study. Head maximum forward displacement 16.5 cm.*

Regarding injury criteria, no relevant injuries were found during the simulation. The following table summarises the most relevant injury risk predictors obtained from simulation.

*Table 2.*
*Predicted injury for the AEB manoeuvre*

| Injury criteria | Value | Probability of AIS2+ injury |
|---|---|---|
| HIC15 | 0,04438 | 0,00% |
| Head 3 ms (m/s^2) | 15,21 | - |
| Neck peak tension (N) | 98,139 | - |
| Chest deflection (m) | 0,00276 | 0,02% |
| Shoulder belt B3 (N) | 382,81 | - |
| Lap belt B5 (N) | 208,68 | 0,00% |
| Lap belt B6 (N) | 201,96 | 0,00% |

According to the predicted values, if the passenger is properly seated and enough room for head and knee displacement is provided, hard impact against the car interior is unlikely to happen, resulting in no injury. This result is as expected as active safety systems have been designed to not generate any injuries and concentrate in avoiding or mitigating the crash event.

**Definition of the test**

In the first stage of the study, the frontal impact load case was selected (Figure 1). The volunteer tests were conducted at IDIADA's proving ground facility which can be seen on Figure 5.

*Figure 5: IDIADA Headquarters Proving ground (L'Albornar, Spain)*

The main goal of these volunteer tests was to create a database of EMG (Electromyography) signals and tracking information relative to the unexpected reaction of the participants to the frontal impact which later will be analysed by means of simulations using HBM. In order to achieve a "surprise" reaction from the participants, the test was set up as a test of comfort and confidence in an automated car depending on the distance between vehicles.

In the test, two consecutive cars made laps in the area shown in the Figure 5. At each lap, the distance between these cars varied, while the participant reported the safety and comfort feelings. The EGO vehicle was driven on the proving ground by professional driver and the volunteer was positioned in the front passenger seat. The volunteer was instrumented with EMG sensors and was being tracked by a series of 2 cameras in order to calculate the final occupant position just before the crash event.

A visual obstacle, balloon car, was placed in the way of the EGO vehicle's route. On the fourth/fifth lap the cut-out maneuver was performed and close to crash event took place. The maneuver can be seen in the Figure 6. The safety of the volunteers was studied by means of feasibility study as previously described.

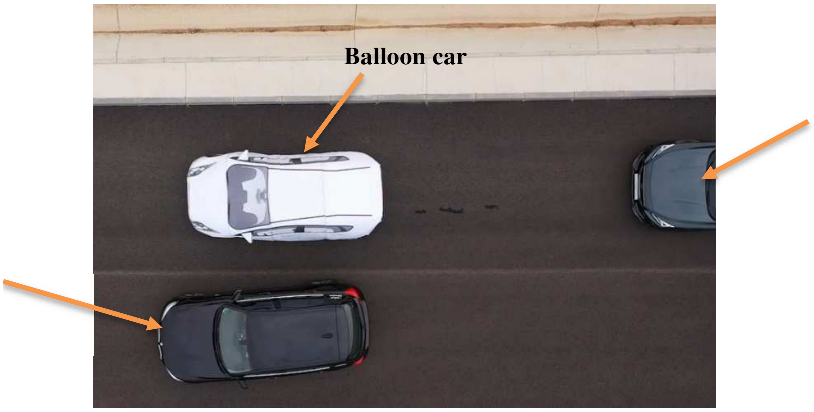


*Figure 6: Cut-out manoeuvre*

The initial velocity of the vehicle was set to 70km/h. A generic deceleration pulse was generated based on three parameters as described in Figure 7:

- A = Pulse activation time. A time of 500 ms was used for the generic pulse as shown in Figure 2.
- B = Brake gradient. A value of 66 $m/s^3$ was used.
- C = Maximum brake acceleration. 1 g was used as described previously.

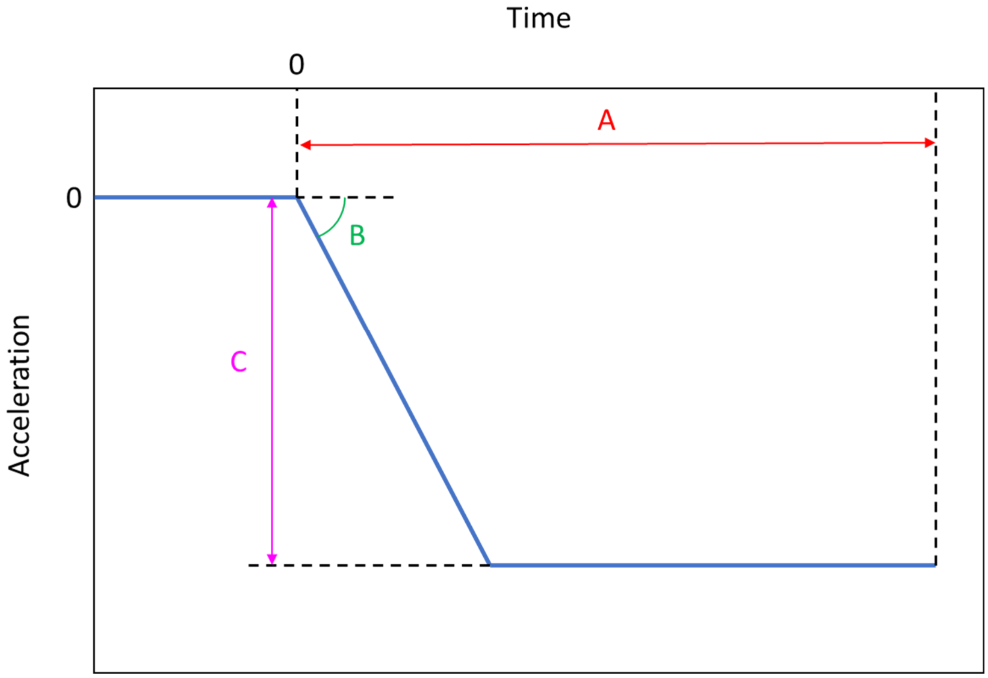


*Figure 7: Generic braking pulse diagram*

An important factor in the tests, to be able to compare the participants' reactions, both in terms of motion tracking and muscle activation, was the repeatability of the braking manoeuvre.

In order to achieve similar deceleration values, the driver of the test vehicle practised the manoeuvre several times until the differences between rounds were reduced as much as possible. In addition, visual reference points were installed on the proving ground to facilitate this task.

## Test preparation

### Electromyography

EMG sensors are designed to monitor muscular activity. In the case of the ISOP study, the muscle activation of a volunteer was measured during the pre-crash event. The sensors and the methodology applied were in accordance with the European SENIAM project [5].

EMG sensors connected to electrodes placed on the skin surface over the corresponding muscle were used to collect the physiological signals. These were connected to the Channel Hub device, with capacity for 8 inputs. A total of 2 Channel Hubs and 16 EMG sensors were being used in all volunteer tests.

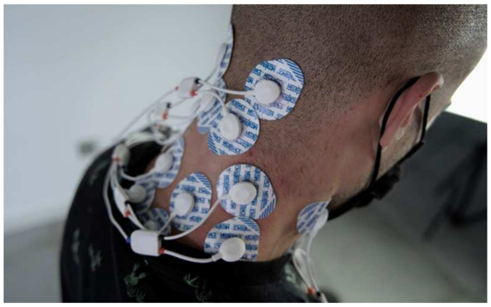


*Figure 8: EMG sensors placement on neck*

Table 3 lists the 16 muscles being monitored in the trunk and neck region, which were considered to be the most significant muscles for this type of study, according to the study done with active HBM subjected to a pre-crash scenario simulation. Upper and lower extremities were not included in the study due to the test limitations.

***Table 3.***
***Muscle selection for the study***

| **Body part** | **Sensor** | **Muscle** | **Primary motion** | **Secondary motion** |
|---|---|---|---|---|
| Trunk | 1 | Erector spinae left | Spinal column extension | |
| | 2 | Erector spinae right | Spinal column extension | |
| | 3 | Rectus abdominis right | Spinal column flexion | |
| | 4 | Rectus abdominis left | Spinal column flexion | |
| | 5 | Medial external obliques right | Spinal column flexion | Lateral trunk flexion |
| | 6 | Medial external obliques left | Spinal column flexion | Lateral trunk flexion |
| | 7 | Lateral external obliques right | Lateral trunk flexion | Spinal column flexion |
| | 8 | Lateral external obliques left | Lateral trunk flexion | Spinal column flexion |
| Neck | 9 | Splenius Capitis left | Neck extension | Lateral neck flexion |
| | 10 | Splenius Capitis right | Neck extension | Lateral neck flexion |
| | 11 | Splenius Cervicis left | Neck extension | Lateral neck flexion |
| | 12 | Splenius Cervicis right | Neck extension | Lateral neck flexion |
| | 13 | Sternocleidomastoid left | Neck anterior flexion | Lateral neck flexion |
| | 14 | Sternocleidomastoid right | Neck anterior flexion | Lateral neck flexion |
| | 15 | Scalenus anterior/posterior right | Lateral neck flexion | |
| | 16 | Scalenus anterior/posterior left | Lateral neck flexion | |

Placement of the sensors is shown in Figure 9.

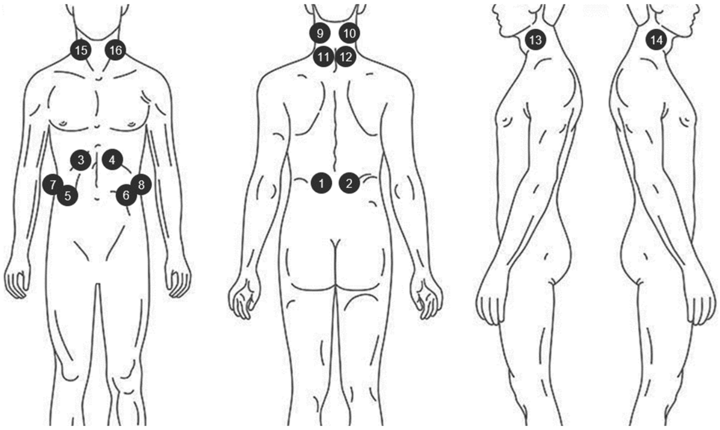


***Figure 9: Volunteer EMG instrumentation***

A calibration process was done with each participant to find the Maximal Voluntary Contraction (MVC) levels. To find the MVC value of each muscle group, specific physical exercises were performed. Figure 10 shows the calibration exercises for the trunk muscles and Figure 11 shows the calibration exercises for the neck muscles.

***Figure 10: Calibration exercise for MVC of rectus abdominis (a), obliquus externus (b) and erector spinae (c)***

***Figure 11:Calibration exercises for MVC of splenius capitis, splenius cervicis, sternocleidomastoid and scalenus***

Trunk contraction exercises lasted 3 to 5 seconds and were repeated four times. Each exercise analyses a single muscle.

For the neck, the procedure was the same, but all the muscles were analysed simultaneously in each exercise. In this case, the help of a person was needed to make the different points of force with the hands so that the participant could apply resistance and activate the musculature.

From the obtained values, the highest value in each case was marked as MVC. To be able to make a later comparison with the HBM this value corresponds to a number 1, being the maximum muscular activation and 0 the total relaxation.

For further analysis, data was exported, and the transfer function was applied (Equation 1).

$$\boldsymbol{EMG(V)} = \frac{\left(\frac{ADC}{2^{n}} - \frac{1}{2}\right) * VCC}{G_{EMG}} \qquad \text{Equation 1 [14]}$$

| | | |
|---|---|---|
| - | ADC | Raw data imported |
| - | n = 16 | Number of channel bits |
| - | VCC = 3 V | Operating voltage |
| - | GEMG = 1000 | Sensor gain |

The results are shown in mV which is just multiplication of the EMG(V) by 1000.

**<u>iMotions</u>**

iMotions software was installed for data collection in the vehicle during the testing with participants. iMotions is an integrated analysis platform made to execute human behaviour research. In this project it served to process and synchronize all data from Open Signals and camera signals.

Open Signals software reads data collected from 16 EMG sensors. This software was integrated into iMotions. Although iMotions displays plotted data at a frequency of 20Hz it recorded it at a frequency of 1000Hz. Sensor cables and Channel Hubbs were taped to the participant's body with medical tape to minimize noise. The data obtained were consistent and synchronized with the recordings obtained by AXIS cameras and can be seen in Figure 12.

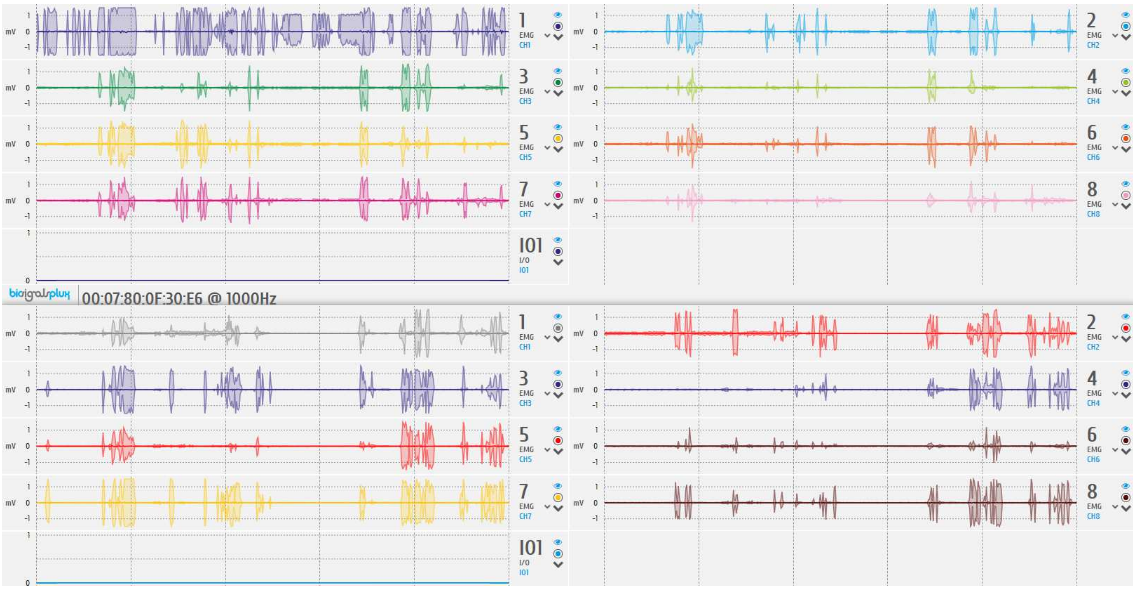


*Figure 12: Example of Open Signals data collection from 16 EMG sensors*

**Tracking**

To be able to obtain the exact position of the critical body regions at T0, a tracking system was implemented in the vehicle. The interior of the vehicle was measured with Krypton measuring system and targets were put to the key points for tracking as can be seen in Figure 13.

A system of 2 high-speed cameras was placed in the interior of the vehicle in order to video record the following targets: shoulder, elbow, wrist, hip, knee and head on the left side of the participant. The targets were white ping pong balls placed on the exact location. The cameras were synchronized with the EMG data by triggering a flash.

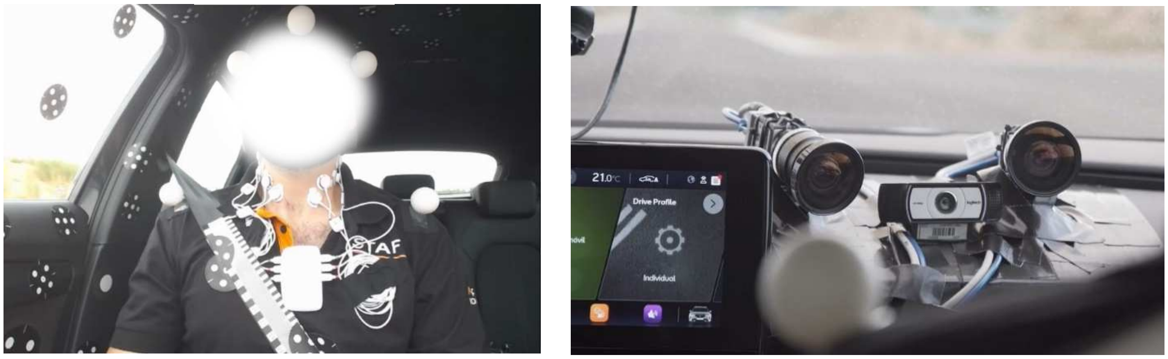


**Figure 13: Right: Tracking targets on vehicle, seat belt and volunteer; left: system of 2 high-speed cameras**

Key points:

- Head: 3 tracking balls (2 lateral, 1 front of the head)
- Shoulders: left and right
- Lap belt: left and right (submarining analysis)
- Wrist: left and right (global movement analysis)

**Figure 14: Tracking targets on volunteer**

**CANape**

GPS data from the EGO vehicle and the support vehicle were collected in both iMotions and CANape. CANape allows exporting mf4 files for analysis with the ADAS department tools.

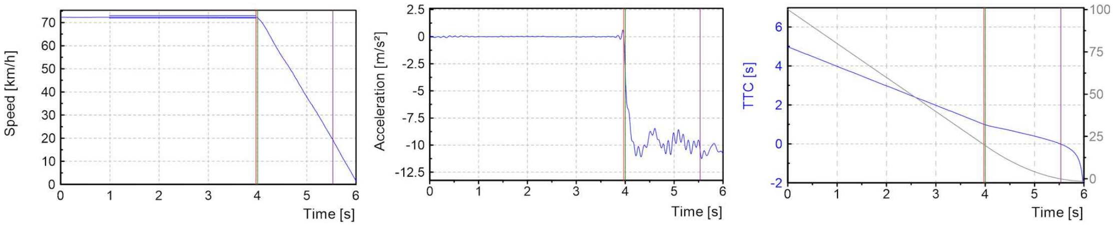


*Figure 15: CANape signals (left: speed; middle: acceleration; right: TimeToCollision)*

**Positioning of the seat and volunteers**

The seat was adjusted to a position which was considered to be the most common and still comfortable for both 50% male and 50% female occupant. This position was measured, and the seat was put on exact point by means of 3D positioning tools. The seat back angle was not altered neither the fore-aft position of the seat during or between the tests. The seat back angle was set to a standard 22.5º and the seat was set to the mid-fore-aft position and mid-height. The correctness of the testing position was controlled visually by checking the marking on both seat and floor as can be seen on Figure 16.

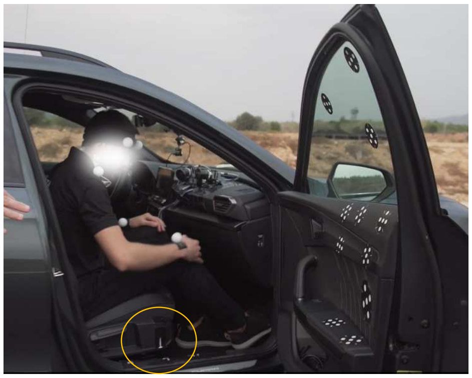


*Figure 16: Fixed seat adjustment: mid-mid, 25º seat back angle*

**TEST RESULTS**

The participants were selected according to the anthropometry which would be the most suitable to represent the THUMS 50% male HBM and ViVA 50% female HBM. The tolerance was set to +/-2kg of weight and +/-5cm of height. Table 4 represents the volunteer selection for the study.

*Table 4: Volunteers data*

| | Sex | Weight | Height |
|---|---|---|---|
| **Participant 1** | M | OK | OK |
| **Participant 2** | M | OK | OK |
| **Participant 3** | F | OK | OK |
| **Participant 4** | M | OK | OK |
| **Participant 5** | M | OK | OK |
| **Participant 6** | M | OK | OK |
| **Participant 7** | F | OK | OK |
| **Participant 8** | M | OK | OK |
| **Participant 9** | M | OK | OK |
| **Participant 10** | M | OK | OK |

Each test was performed with the 3 main investigation points: muscle activation, tracking and information about the vehicle. Table 5 shows the evolution of the tests, where some of the measured quantities failed.

*Table 5: Tests database*

| | Sex | iMotions | CANape | Tracking |
|---|---|---|---|---|
| **Participant 1** | **M** | NOK | NOK | NOK |
| **Participant 2** | **M** | OK | OK | OK |
| **Participant 3** | **F** | OK | OK | NOK |
| **Participant 4** | **M** | OK | OK | OK |
| **Participant 5** | **M** | OK | NOK | NOK |
| **Participant 6** | **M** | OK | OK | NOK |
| **Participant 7** | **F** | OK | OK | NOK |
| **Participant 8** | **M** | OK | OK | OK |
| **Participant 9** | **M** | OK | OK | OK |
| **Participant 10** | **M** | NOK | NOK | NOK |

Out of the 10 volunteer tests, only 4 could be subjected to the whole spectrum analysis.

**EMG analysis**

Muscle activation data was collected during the braking manoeuvre. The following graphs show an example of the muscle activation collected from Participant 3.

In Figure 17 can be seen the activation of the neck and activation of the trunk. Analysing the EMG signals together with the video / tracking analysis, the following could be concluded. During the first moments of the braking event, the volunteer was moved towards the interior of the vehicle, activating the neck muscles. Following movement was bracing towards the seat back activating the trunk muscles. The whole sequence can be seen on Figure 18.

All participants showed consistency in the muscle activation with what is perceived through the video, so with this preliminary analysis, we can consider that the data acquired will be able to provide valuable information on the occupant's behaviour.

One drawback that was observed is that the muscle activation arrived with a delay of approximately 1 second. This problem will have to be solved in further tests in order to have an exact synchronisation.

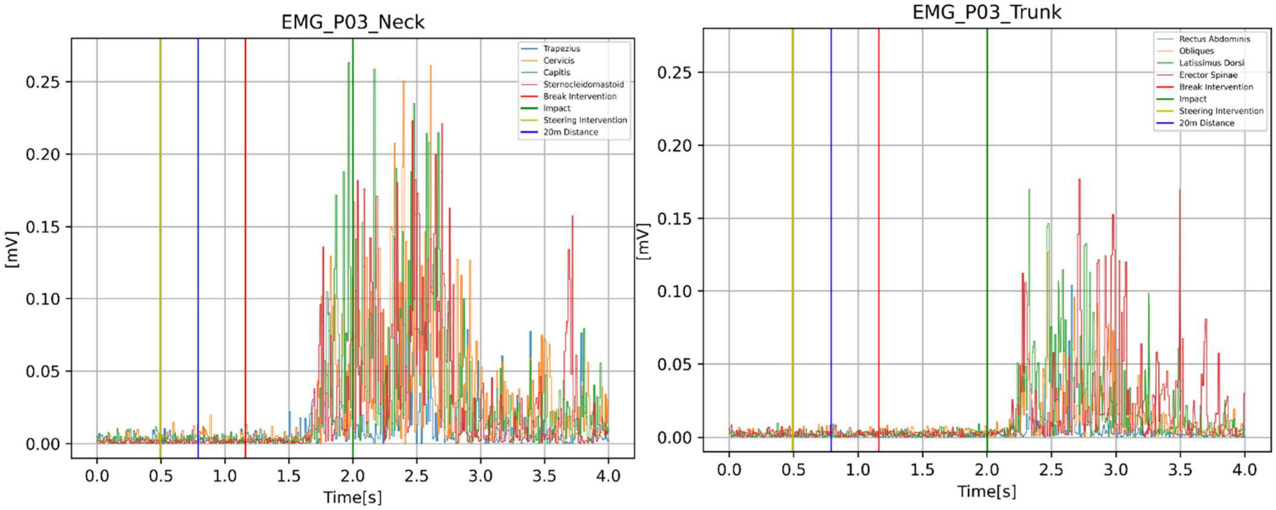
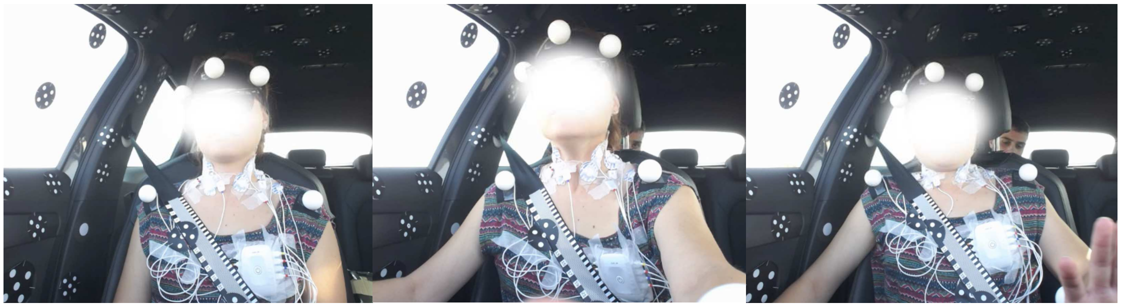


*Figure 17: EMG neck and trunk signals from volunteer n.3*



T = 0s T = 2s T=3s

*Figure 18: Video sequence analysis of volunteer n.3: left = relaxed, middle = neck activation + forward movement, right = trunk activation + rearward movement*

**Video tracking analysis**

The Tracking analysis consisted in a dynamic photogrammetry measurements, a mathematical calculation methodology using images from video as source of information. For the 3D analysis, 2 calibrated cameras were needed, measuring 3D reference and targets. The camera calibration transformed the image into a bounded plane where all the pixels/image points were geometrically controlled.

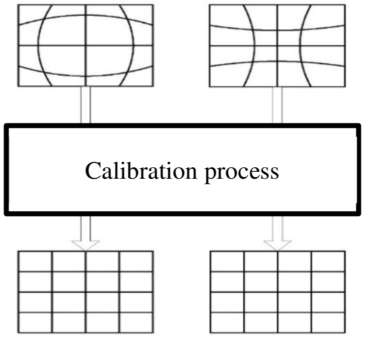


*Figure 19: Video calibration process*

Those cameras need 15-30 degrees between them in order to intersect their projections onto the image plane.

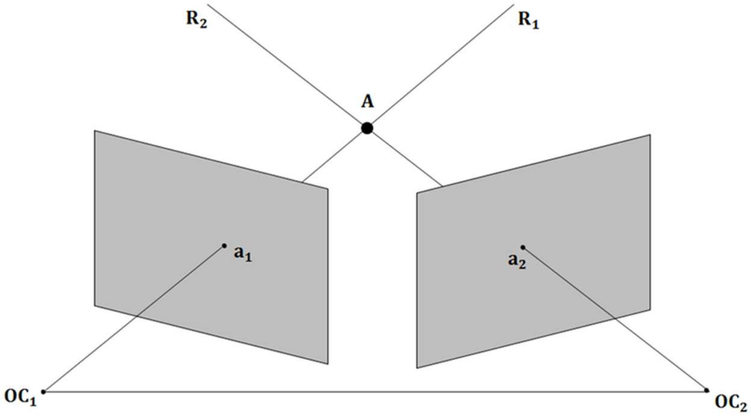


*Figure 20: Projection onto the image plane*

| | |
|---|---|
| OC1: | Optical center of camera 1 |
| OC2: | Optical center of camera 2 |
| R1: | Target projection from optical center onto image planes |
| R2: | Target projection from optical center onto image planes |
| A1: | 2D position in camera 1 plane |
| A2: | 2D position in camera 2 plane |
| A: | Target 3D position |

The interior of the car was full of measured 3D targets to be used as reference, defining the coordinate system and avoiding the camera vibrations because those targets were also tracked.

*Figure 21: Measurement of the hard points (in the vehicle interior) and movable targets (on participant)*

The final step of this phase of the project is to combine the EMG data with the video analysis and calculate the maximum displacement of the volunteer after applying the pre-crash braking.

**NEXT STEPS**

All the data from the volunteer testing will be analyzed in next months and from the preliminary analysis already done, the need of more statistically significant valid test sample has been identified.

The scope of the project ISOP is not limited only to the volunteer testing, but as was mentioned earlier in the paper, simulations with THUMS and ViVA HBMs are on-going and the results will be available in following months. The goal is to understand the influence of the pre-crash maneuvers on the safety of the current state-of-the art restraint systems.

In the previous phase of the project, several tests were performed in IDIADA's driving simulator which will be analyzed and compared with the volunteer testing in the proving ground. Both testing protocols are following the same methodology.

## LIMITATIONS

Injury risk evaluation with ATDs (Anthropometric Test Devices) is being used in crash testing protocols and for the development of safety systems for decades and builds a common and accepted base in the industry as well as legislation for the assessment of occupant safety.

However, ATDs are not validated nor developed for being subjected to the pre-crash manoeuvres or new seating configurations such as reclined positions. Moreover, there doesn't exist any ATD with muscle activation, which is essential while investigating engagement of the occupant in the pre-crash and in-crash phase.

In contrast to ATDs, some virtual HBMs (human body models) realistically represent the anatomic structure of the human including bones, flesh, skin, fat, and soft tissue. The high model detail allows a direct assessment of the injury risk based on the damage applied to the respective body region (e.g., in form of stress or strain), assuming a correct damage prediction of the model. However, human body models are not yet validated and are still under the study and development.

During the study, several limitations connected to the methodology were identified, such as reliable tracking system, data collection system, etc. and therefore for the next volunteer testing, new systems will be evaluated and selected.

## CONCLUSIONS

Nowadays, the emphasis is done not only to minimize the fatalities or to lower the severity of the injuries during the crash events but also to prevent the impacts from occurring at all. These pre-crash systems and manoeuvres however are altering the optimal position of the occupant to which the state-of-the art restraint systems are developed.

The active response of the occupant to unexpected impact can result in decreasing the effectiveness of the state-of-the art restraint systems. Therefore, it is essential to understand the scope of this influence.

IDIADA has been working on creating the protocols for testing with volunteers in proving ground as well as in the driving simulator in order to create a database with information from EMG data collection, tracking data and vehicle manoeuvre data. Once the protocols have been created and validated, several tests have been performed with volunteers representing 50% male and 50% female occupants.

The project ISOP has established a methodology for pre-crash manoeuvre testing which could be later used to enlarge the database and to add even more anthropometries in order to cover most of the population.

A safety feasibility study using MADYMO HBM showed that with the deceleration of 1g, the expected forward displacement of the passenger is about 17cm. This value will be compared in the next phase of the study with the data from tracking analysis.

From the performed test it is clear that new technologies need to be explored for more reliable data acquisition.

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