# THE RESPONSE OF HYBRID III, EUROSID AND VOLUNTEER IN THE FIRST PHASE OF A ROLLOVER ACCIDENT

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Paper Number 05-0254

## ABSTRACT

In rollover crashes there is a high risk for occupants to suffer severe injuries. The number of rollovers tends to increase at present presumably because of the increasing number of cars with a relatively high COG (Minivans, MPVs). Therefore there is a great potential for injury reduction in that area. Available dummies are designed and validated for front, side or rear impacts but not for complex events like rollovers. So the question comes up which Dummy should be used to assess safety systems for rollover accidents.

The aim of the study was to get a detailed information of the dummy behaviour compared to human behaviour in the first phase of a rollover accident.

Series of measurements with volunteers and dummies (Hybrid III and EuroSID) were carried out by using a current car seat mounted on a sled with additional tilting mechanism. Two types of motion were imposed to the sled that represented different rollover scenarios: a pure translational motion and a pure rotational motion. Two different acceleration levels from the range found in real world crashes were used. The kinematics of dummies as well as kinematics and muscle activity of volunteers were analysed.

The results show a significant difference between the kinematics of dummy and volunteer. In the rotational sled motion the volunteer movement was directed to the opposite side compared to the dummy. Thus, the dummies do not represent human occupants very well. Furthermore, the kinematics of both dummies is very similar, so no preference regarding the dummy type can be recommended. The EMG revealed activity of all observed muscles in all test configurations, the muscle activity influences evidently the movement of human occupants. This results are suposed to be useful for the development of rollover dummies and advanced numerical occupant models.

## INTRODUCTION

The objective of this work was to assess the kinematics of the occupant in the first phase of roll. The knowledge of occupant kinematics is essential for the design of new restraint systems or for the trimming of current systems for rollover accidents. Current restraint systems like curtain airbags and belt pretensioners have the potential to prevent severe injuries in rollover accidents. But these systems need a correct timing of triggering to be effective. If the occupant is already out of position when the restraint system is triggered the system may have no effect or even worse may lead to injuries of the occupant. This demonstrates the importance of the occupant kinematics during the first phase of the roll for the assessment of possible out of position issues.

As opposed to most frontal, rear or side crashes the accelerations acting on the occupants in rollover accidents are usually lower and the duration of the crash is much longer (up to several seconds). Thus, the kinematics of the occupants can be influenced by muscular actions (both reflexive and voluntary).

Series of experiments with volunteers and dummies were carried out on a motion base that simulated the first phase of a roll. The kinematics were measured by a 3D motion capturing system, the activity of selected muscles of the volunteers was measured via surface EMG.

The experiments were designed to answer following questions:

- Do the occupants exert active muscle forces during the first phase of roll?
- In what regions are muscles activated?
- Is the muscle reaction side-specific (i.e. are there differences between the left and the right hand side of the same muscles)?
- Does the muscle activation clearly influence the kinematics of the occupant? How and to what extent?
- Does muscle activation (its level or time pattern) depend on the magnitude of the accelerations the body is exposed to?
- Does the occupant kinematics depend on the magnitude of the acceleration the body is exposed to?
- Are there interindividual differences in the occupant kinematics?
- Are there differences between the kinematics of volunteers and dummies (HybridIII and SID)?
- Which of the two used dummies is more suitable for the usage in rollover-like scenarios?

## METHODS

### Experimental Setup

In order to imitate the car motion in the first phase of roll a special sled facility with a mounted motion base has been constructed by TUG in co-operation with LMU. The sled was allowed to move on rails fastened firmly to the ground. A motion base (i.e. a steel frame with wooden platform) was anchored to the sled by a hinge so that tilting movement of the platform was possible. A current make of a car seat with integrated seat belt was firmly screwed to the motion base. For safety reasons a safety frame with tight net was attached on both sides of the motion base (see Figure 1).

Two motion types were simulated by using the motion base that represent the dominant features of different rollover scenarios – translational movement (rollover scenarios with dominant lateral acceleration in the first phase – trip over, turn over, collision with another vehicle) and tilting movement (rollover scenarios in which the roll is not accompanied by significant lateral acceleration – flip over, fall over).

The translational movement was imitated by using the principle of inverse motion. It means that instead of inducing an initial velocity to the sled and braking it as it would be in the real car, the sled was exposed to the same lateral acceleration (originally deceleration of the car) in a resting position. The sled thus moved in the opposite direction than the (assumed initial) movement of the car, but the effects on the occupant are exactly the same. The translational movement of the sled was driven by a bungee rope, the acceleration of the sled was trimmed by adjusting the initial pull-strength of the rope.

**Figure 1. The motion base with a seated volunteer.**

The tilting movement of the motion base was driven by a pneumatic piston; the tilting velocity was determined by the initial air pressure. In this configuration the motion base stood still and only the tilting movement was induced.

The whole experimental set-up was designed to minimise all potential hazards for the volunteers. An approval of the ethics commission of the LMU was obtained in advance.

Prior to the experiment, each volunteer got an explanation of all procedures and signed an informed consent. His basic anthropometric data were collected and he put on a tight non-reflective dress.

The skin over chosen muscles was shaved and rubbed with EGM-preparation gel for better conductivity. The Blue Sensor®electrodes were positioned over the thickest part of the selected muscles (overview see Table 1).

Fourteen reflective markers for the kinematical analysis were positioned on the volunteers body as depicted in Figure 2. Please note that the list contents only the markers needed for the analysis, some more were used to facilitate the automatic tracking process. The same set of markers was used for the dummies as well.

**Table 1.**
**Muscles selected for the EMG analysis.**

| Muscle | Function |
|---|---|
| m. sternocleidomastoideus left | head rotation to the right, head tilt to the left |
| m. sternocleidomastoideus right | head rotation to the left, head tilt to the right |
| m. trapezius left | adduction, stabilisation of the shoulder girdle |
| m. trapezius right | adduction, stabilisation of the shoulder girdle |
| m. obliqus externus abdominis left | lateral flexion of the torso to the left |
| m. obliqus externus abdominis right | lateral flexion of the torso to the right |
| m. rectus femoris left | knee extension, hip flexion |
| m. rectus femoris right | knee extension, hip flexion |

Based on the position of the real marker, the position of the so-called virtual markers was computed automatically. These points enhanced the analysis of the subjects movements.

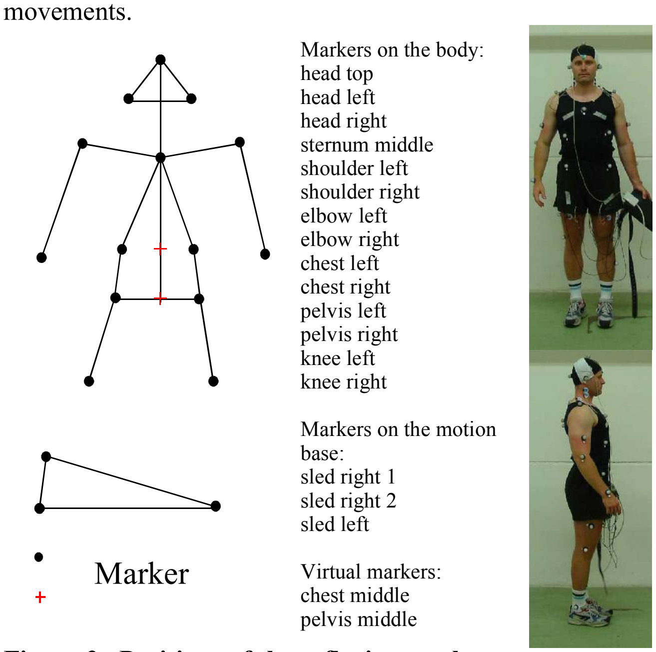


**Figure 2. Positions of the reflexive markers on the volunteer's body.**

Because of time and cost limitations, experiments were carried out with two volunteers, a HybridIII and a EuroSID dummies only. The test matrix showing the overview of experiments carried out in the movement science lab is depicted in Table 2.

The variants slow and fast in table 1 are stated in inverted commas because we were not able to reproduce exactly the quickness of the translational and rotational motion for all occupants. Though both bungee rope and pneumatic piston enabled the regulation of the motion to a certain degree, the kinematics of the sled motion were not exactly reproducible. On the other hand, a construction of a sled facility with a high degree of reproducibility would have been much more consuming in terms of time and resources and the results achieved with our motion base proved to be meaningful. The acceleration levels in the experiments were chosen so that they comply with two requirements – they should represent the accelerations observed in the first phase of real rollover accidents and at the same time the experiment had to be safe for the volunteer. The peak lateral (inertial y-) accelerations achieved during the translational movement as well as the peak roll-rates achieved during the rotational movement are listed in table 3.

**Table 2.**
**Experimental matrix.**

| Occupant | translational movement | | rotational movement | |
|---|---|---|---|---|
| | „slow“ | „fast“ | „slow“ | „fast“ |
| volunteer 1 | X | X | X | X |
| volunteer 2 | X | X | X | X |
| Hybrid III | X | X | X | X |
| EuroSID | X | X | X | X |

**Table 3.**
**Peak accelerations/roll-rates of the motion base in the experiments.**

| Occupant | y- acceleration peak (g) | | roll-rate peak (grad*s$^{-1}$) | |
|---|---|---|---|---|
| | „slow“ | „fast“ | „slow“ | „fast“ |
| Volunteer 1 | 0.8 | 0.9 | 56 | 62 |
| Volunteer 2 | 0.7 | 0.9 | 36 | 60 |
| HybridIII | 0.6 | 1.0 | 44 | 58 |
| EuroSID | 0.9 | 1.0 | 55 | 64 |

The peaks stated in table 3 were found from filtered kinematical data (low-pass filter with cut-off frequency 15Hz). It should be noted that acceleration data are computed as second derivative of marker positions and as such they are extremely sensitive to filtering. Different filter may have lead to different peak values.

Our experimental values are comparable to real data. However, one has to keep in mind that rollover accidents distinguish themselves with a very wide variety of kinematics (not only the heights of the accelerations vary in time, but also their directions) and as a result only a small part of possible scenarios has been dealt with.

The experimental peak values correspond well with the lower values of reconstructed accidents and are thus realistic. Higher accelerations and/or roll rates would have been dangerous for the volunteers.

In all experiments the occupant was seated and the seat belt properly fastened. After a check-up of all safety measures and a proper function of all measurement devices the propulsive devices were loaded (bungee rope pulled or pneumatic piston filled with air). The motion of the sled followed after a countdown, the volunteers were aware of the motion onset.

For each occupant at least two measurements were carried out for each motion, i.e. the slower and the faster modus.

**Instrumentation**

The surface EMG was measured by using an 8-channel telemetric measurement device (NORAXON, Scottsdale, Arizona). The measurement was triggered simultaneously with the kinematical analysis system by the same external trigger.

For the kinematical analysis the EVa Real Time 2.1 (Motion Analysis, Santa Rosa, California) motion capturing system was used with 8 Falcon cameras. The recording frequency was set at 240Hz. The positioning of the cameras as well as the calibration of the measurement space was done according to the recommendations of the system manufacturer.

**Evaluation and Analysis**

The EMG Data were rectified and plotted at the same time and voltage scale in order to facilitate the assessment of the total amount of muscle activity. Because the position of the electrodes did not change between various test runs, it is possible to evaluate activation differences of the same muscles in various situations. However, a comparison between various muscles of the same subject is not possible because of likely differences in the amounts of muscle units recorded.

The trajectories of the markers on the subject's body and on the motion base were tracked by using the EVa software and low-pass filtered with a cut-off frequency set at 15Hz. The positions of the virtual markers were computed in the system as defined by the investigator.

For the presentation of the occupant kinematics, screenshots from the animations have been made in the overall (near to frontal) view and in the top view (xy plane).

## RESULTS

### Translational Movement

**Muscle Activity Analysis**

Both subjects showed a considerable amount of muscle activity during the simulated first phase of roll in the slow as well as in the fast variant of the test. Active were apparently all the considered body regions – the neck, abdomen as well as the legs.

The onset time of muscle activity does most likely not depend on the quickness of the movement of the sled – we have found approximately the same values for the slow and the fast variants in both tested subjects. The fastest response show the neck muscles (sternocleidomastoideus) with the onset at approx. 0.1sec. A little bit slower reaction time has been found for the abdomen muscles and the upper leg muscles followed with a minor delay (reaction time up to 0.2sec). The response of the trapezius muscle was inconsistent and varied between 0.1sec and 0.2sec.

These findings correspond to our expectations – the neck muscles react first because the head is accelerated with respect to the torso and the muscular actions are presumably aimed at its stabilisation. The stabilisation of the torso follows and because the legs are supported on the floor, no actions are needed until the torso has deviated from its upright position.

Though the translational movement of the sled was oriented from the left to the right hand side of the sitting subject, relatively little lateral differences in the muscle activation were found. The abdominal muscles showed about the same reaction on both sides in both subjects. It means that the muscles stabilise the torso regardless of the direction of acting forces (accelerations). The neck muscles showed concurrent activation as well. However, in the first subject there was completely the same activation onset time on both sides of the body whereas in the second subject there was a shift towards the right hand side (i.e. the right muscle was activated earlier and a concurrent activity followed, see Figure 3). It is apparent as well that there is more activation on the right hand side at the beginning of the movement – the muscle counteracts the tendency of the head to move to the left. After approximately 0.2sec there is no difference between the left and the right hand side of the neck musculature.

Also evident from Figure 3 is a higher amount of muscle activity in the faster variant of the movement. Though it is impossible to quantify the force exerted by the muscles (that is only to a certain degree possible in isometric contractions), the amount of muscle activity can be compared because the positions of the electrodes were exactly the same for both measurements. These results are also plausible, because higher sled accelerations bring about higher accelerations of the head and therefore more muscle force is required for stabilising.

Similar tendency (i.e. more muscle activation in case of higher accelerations) has also been observed in other muscles except for the upper leg muscles.

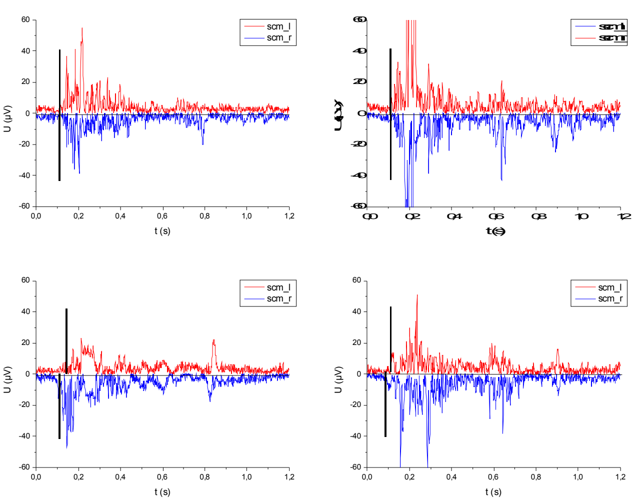


**Figure 3. EMG of m. sternocleidomastiodeus left (red) and right (blue); top row: Volunteer 1, slow (left) and fast (right) motion of the sled; bottom row: Volunteer 2; left column: slow (left) and fast (right) motion of the sled.**

### Occupant Kinematics Analysis

The kinematics of all measured occupants (volunteers as well as dummies) recorded as 3D – Trajectories of selected points on the surface of various body segments is a very complex phenomenon. A simple synchronisation of all trials does not make sense because accelerations induced to the sled vary and the sled position as well as acceleration level in various trials differ one from another at the same point of time. Thus, two space locations of the sled were chosen and the positions of the occupant at these configurations were evaluated. The sled locations were chosen approximately at the beginning and at the end of the sled acceleration phase, the sled travelled 0.76m between the two screenshots. In the following, only the most interesting screenshots are presented, the complete set of pictures from all measurement runs can be found in the attachment.

It is apparent from the figures that only very little movement of the head and shoulder relative to the hip and chest occurs. Volunteer 1 as well as both dummies stayed with their trunk and head upright, only volunteer 2 showed some bending in the trunk. It means that there is most probably a high degree of interindividual variability in the response of human subjects to low lateral accelerations. Different kinematics of both volunteers corresponds well with the deviations found in the EMG singnal as discussed above.

The dummy response met our expectations – both dummies are too stiff in the neck and shoulder region and tip over without bending the neck. With higher accelerations the trend observed in volunteer 2 would probably become more apparent in both volunteers whereas the dummy response would most probably stay the same. Because of safety reasons it was impossible to expose the volunteers to higher accelerations.

No noticeable rotation about the longitudinal axis was found in any of the evaluated segments in all occupants, no signs of movement forward or backward of the upper torso or the head were recorded. Thus, in this scenario the movement of the occupant can be considered planar in the frontal plane.

With respect to crash testing there is no preference regarding the dummy type to be used – both Hybrid III and EuroSID show the same (very stiff) behaviour.

## Rotational Movement

### Muscle Activity Analysis

Similarly to the translational movement, all the selected muscles responded to the rotational motion of the sled. However, some differences in the response have been observed.

The onset of the muscle activity corresponded roughly to the one found in the translational movement except for the upper leg muscles which were activated significantly later in the second volunteer. The most striking difference between the two volunteers has been found in the activation of the m. obliquus externus abdominis as shown in Figure 4.

Whereas the first volunteer activates the muscles on the left hand side of the body much sooner than on the other side, there is no lateral difference in the response of the abdominal muscles in the second volunteer. These reactions show two different strategies of the human subjects:

- An active effort to stabilise the trunk by means of concurrent muscular actions on both sides of the trunk (the second volunteer).

- Bending of the torso actively back to the vertical position after its deviation due to the sled rotation (the first volunteer). The tilting motion of the sled was oriented clockwise from the point of view of the subject so the left hand side of the abdominal musculature was employed in the correction.

In spite of the huge difference between the left and right side found in the first volunteer in the abdominal muscles, all other muscles have shown exactly the same activation timing. The effort of the subject was possibly concentrated on the straightening of the torso whereas other body regions were stabilised.

The concurrent activity of abdominal muscles of the second volunteer was in turn followed by higher activity of the left hand side musculature of the neck (m. trapezius) and legs (m. rectus femoris). Thus, this subject corrected presumably the position of the head more in the shoulder region as opposed to the first volunteer.

A minor increase of the activation volume can be observed with higher sled acceleration in all measured muscles.

As mentioned above, it is impossible to assess quantitatively the amount of muscle activation in various muscles. Any conclusion regarding the exerted muscle forces and their influence on the kinematics of the subjects would therefore be misleading. However, the measurements provide valuable information about the response of human subjects to the movements in the first phase of roll.

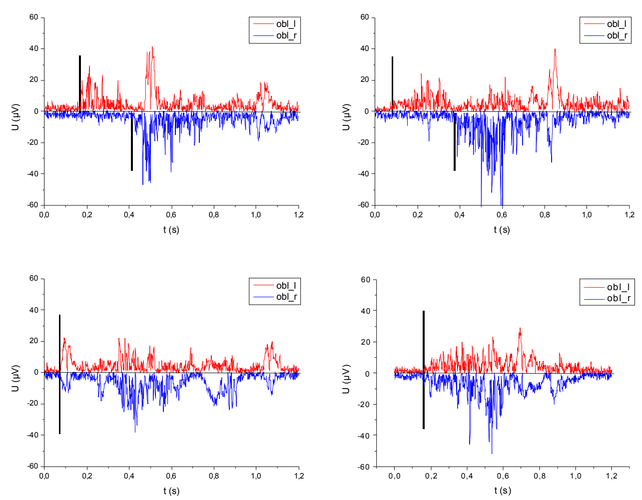


**Figure 4. EMG of m. obliquus externus abdominis left (red) and right (blue); top row: Volunteer 1, slow (left) and fast (right) motion of the sled; bottom row: Volunteer 2; left column: slow (left) and fast (right) motion of the sled.**

## Occupant Kinematics Analysis

It is important to note that though the rotational movement of the motion base represented the first phase of other rollover types as discussed above, the overall rollover direction stayed the same (i.e. if a car would slide laterally as simulated by the translational movement, it would roll in the same direction as simulated by the rotational movement).

The kinematics of both dummies were according to our expectation the same as in the translational movement – their whole bodies just tipped over in the direction of the motion base rotation without any relative movement in the torso or neck regions. As apparent from the figures, there are no differences between the two dummies. Consequently, no preference regarding the usage in a rollover crash-testing can be recommended.

There were significant differences found in the kinematics of human subjects between the translational and rotational movement of the motion base. The bending of the torso and neck is oriented opposite to the one found in the translational movement. Figure 5 shows the comparison between the two movement types in volunteer 2.

In the fast variant of the test the bending of the upper torso and neck becomes even more pronounced.

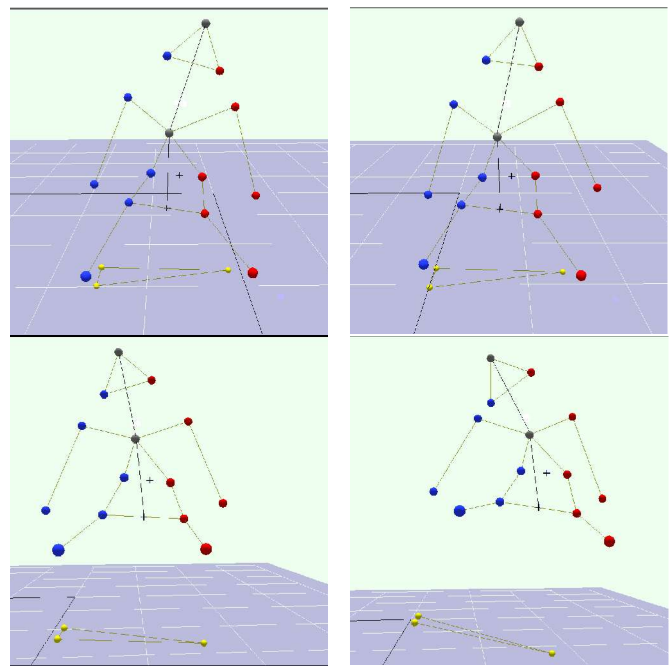

**Figure 5. Bending in the torso and neck regions in volunteer 2 in the translational (up) and rotational (down) movement of the motion base, the early (left) and late (right) phase of the measurement, fast variant.**

Though the above described lateral flexion of the upper torso and the neck occurs in both volunteers, the situation is similar to the one found in the translational movement, i.e. volunteer 1 tends to stay more in an upright position and the bending is only slightly indicated whereas volunteer 2 shows a much higher range of flexion. This fact is probably interrelated with the differences found in the muscle activation as described above and it indicates a huge interindividual variability of the response in human subjects.

The orientation of the shoulder, chest and hip regions did not change. The initial positions of the head markers were checked as well and deviations of the marker placement were excluded. The head of both volunteers rotates from the initial position and the rotation angle increases with time and/or rotation angle of the motion base.

Figure 6 shows the difference in the head/neck and upper torso bending between the volunteers and the dummies in the late phase of the rotational movement. Evidently, the volunteers exert lateral flexion so that the head bends against the direction of the roll whereas the head of the dummies stays in parallel with the longitudinal axis of the body. The relative movement of the head shows thus opposite direction. Please note that for practical reasons the positions of the markers on the volunteers differ slightly from the dummies so the points on the top view do not overlap completely. However, the relative movement of the segments of interest is demonstrated very clearly.

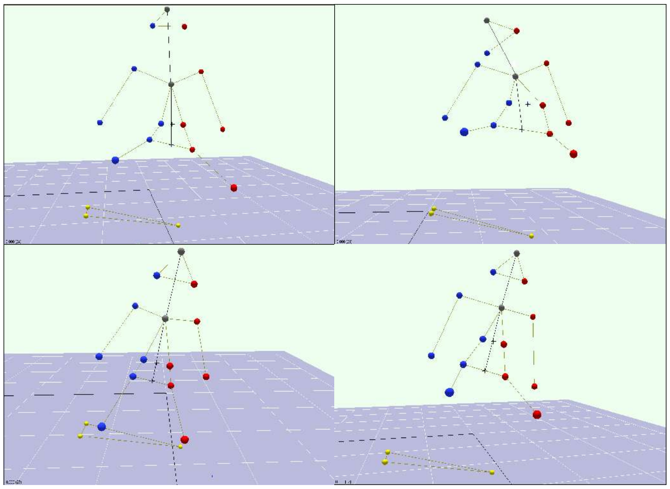

**Figure 6. Difference in the lateral flexion of the head and upper torso of the volunteers and the dummies – late phase of the fast rotational movement. Top left volunteer1, top right volunteer 2, bottom left Hybrid III, bottom right EuroSID**

## CONCLUSIONS

- Both volunteers exerted in all tests active muscle forces, i.e. active movements of the occupants in the first phase of roll are very likely.
- Muscle activity was registered in all regions taken into account
- Differences between the activity of the left and the right hand side of the same muscles were found, i.e. the direction of the movement influences the muscle activation pattern.
- The muscle activity influences the kinematics of the occupant. The response to various movements (rotational versus translational movement) is different.
- With increasing accelerations the response pattern does not change significantly, but the volume of muscle activity increases.
- The relative movement of the shoulder and head/neck regions (i.e. lateral flexion) in the rotational and translational motion differ substantially from each other – the directions of the lateral flexion are opposite. The occupant kinematics is thus highly dependent on the rollover type.
- The occupant kinematics does not change substantially with increasing acceleration (i. e. the same trends can be observed), but the trends become more apparent.
- There is a high degree of interindividual variability in the occupant kinematics.
- Relevant differences were found between the kinematics of human subjects and the dummies.
- Both the Hybrid III and the SID dummies show the same kinematics in the first phase of roll. Therefore, there is no preference with respect to their usage in rollover scenarios.


## ACKNOWLEDGEMENT

This work was performed within the Project „Improvement of Rollover Safety for Passenger Vehicles“ funded by the European Community within the 5th Framework-Programme “Growth” under the contract number G3RD-CT-2002-00802.