THE OCCUPANT KINEMATICS IN THE FIRST PHASE OF A ROLLOVER ACCIDENT – EXPERIMENT AND SIMULATION

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ABSTRACT

The aim of this study was to assess the potential of various hardware dummies (Hybrid III and EuroSID II) and the numerical human model to study rollover situations. Significant differences were found between the kinematics of volunteers in comparison with both Hybrid III and EuroSID II dummies. The numerical simulation with the Hybrid III model corresponds well to the measurement results with the hardware dummy, the simulation with human model shows different kinematics of the occupant which is closer to the one of the volunteers.

Keywords: Rollover Accidents, Human Model, Hybrid III, EuroSID, Volunteers

FOR THE DESIGN AND TRIMMING OF RESTRAINT SYSTEMS information about the occupant kinematics during crashes is necessary. In a typical front or side impact situation the response of the occupant can be represented by crash test dummies fairly well. Rollover accidents are much more difficult to handle because of their multidirectional character. They are designated by long duration (up to several seconds) and low acceleration levels (typically many times lower than in front or side impacts). On top of that, many rollover accidents have been reported where a severe impact (to another car, road infrastructure, a tree etc.) follows after a long pre-crash phase with relatively low acceleration levels. Under such circumstances, even subtle differences in the joint and material properties play an important role. Moreover, muscle activity is likely to influence the occupant kinematics.

For the above mentioned reasons it is obvious that none of the currently available dummies is likely to represent the human occupant well. Previous studies have shown that there is a significant difference between the kinematics of the dummy and the human occupant model in a rollover-crash simulation (Praxl et al. 2003). However, without a direct comparison to the real human occupants it is impossible to assess the biofidelity of both. For obvious reasons it is impossible to measure the response of human occupants in a severe crash situation; that's why typical rollover pre-crash situations were imitated on the sled and analyzed. Moffatt et al (1997) compared the kinematics of Hybrid III, PMHS and volunteers during a test designed to simulate the airborne phase of a rollover accident and investigated the effects of restraint systems on head excursions. He found significantly less lateral motion of the dummy in comparison to the PMHS. Also the vertical head excursion in static tests was lower in the dummy than in the PMHS and the volunteer.

The aim of this study was to investigate the occupant kinematics in the first phase of a rollover accident by means of measurements with volunteers, to assess the kinematical response of various hardware dummies (Hybrid III and EuroSID II) to study similar situations, and, last but not least, to explore the potential of MADYMO occupant models to represent the real humans in rollover-like situations.

METHODS

EXPERIMENTAL SETUP

A special sled facility with a mounted motion base has been constructed in order to imitate the movement of a car in the first phase of a rollover accident. The sled moved on rails fastened firmly to the ground. A motion base (a steel frame with a wooden platform) was anchored to the sled by a hinge so that tilting movement of the platform was possible in addition to the translational movement of the whole sled. A current make of a car seat with integrated seat belt was firmly attached to the motion base. For safety reasons a safety frame with a tight net was attached on both sides of the motion base (see Fig. 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, i.e. 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 standstill position. Thus, the sled moved in the opposite direction than the (assumed initial) movement of the car, but the effects on the occupant were 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. 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.

Fig. 1 - The motion base with a seated volunteer

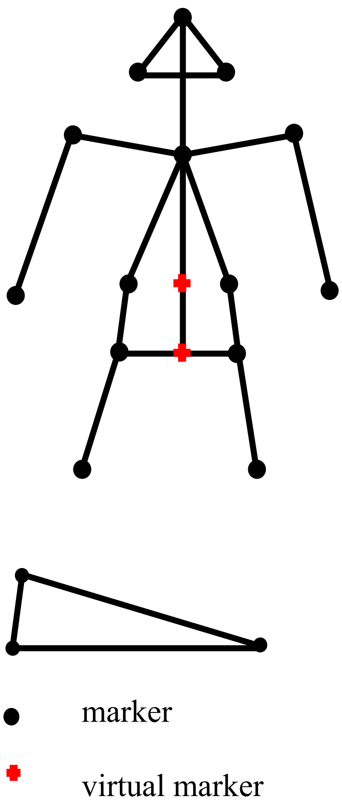
The whole experimental set-up was designed to minimize all potential hazards for the volunteers. An approval of the ethics commission of the LMU was obtained in advance. Prior to the experiment, each volunteer got an explanation of all procedures and signed an informed consent. His basic anthropometric 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: m. sternocleidomastoideus left and right, m. trapezius left and right, m. obliquus externus abdominis left and right, and m. rectus femoris left and right. 14 reflective markers for the kinematical analysis were attached on the volunteer's body as depicted in Fig. 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 both tested dummies as well (Hybrid III and EuroSID).

Based on the position of the real marker, positions of the so-called virtual markers were computed automatically. These points enhanced the analysis of the occupant's movements. 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 1.

Occupant	translational movement		rotational movement	
	“slow”	“fast”	“slow”	“fast”
Volunteer 1	X	X	X	X
Volunteer 2	X	X	X	X
HybridIII	X	X	X	X
EuroSID	X	X	X	X

Table 1. Experimental matrix



markers on the body:
1. head top
2. head left
3. head right
4. sternum middle
5. shoulder left
6. shoulder right
7. elbow left
8. elbow right
9. chest left
10. chest right
11. pelvis left
12. pelvis right
13. knee left
14. knee right

markers on the motion base:
1. sled right 1
2. sled right 2
3. sled left

virtual markers:
1. chest middle
2. pelvis middle

Fig. 2 - Positions of the reflexive markers on the volunteer’s body

The variants slow and fast in Table 1 are stated in inverted commas because the quickness of the translational and rotational motion was not exactly reproducible for all trials. 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.

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 as documented by the accident reconstruction and the field tests carried out within the ROLLOVER Project (Shared-cost RTD GRD2-2001-50086 “Improvement of Rollover Safety for Passenger Vehicles”, Competitive and sustainable growth programme) and, at the same time, the experiment had to be safe for the volunteers. 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 2. The motion base rotated up to 15 degrees.

Occupant	y- acceleration peak (g)		roll-rate peak (degree*s^{-1})	
	"slow"	"fast"	"slow"	"fast"
Volunteer 1	0,8 (2,0)	0,9 (2,5)	56	62
Volunteer 2	0,7 (2,1)	0,9 (2,8)	36	60
HybridIII	0,6 (1,3)	1,0 (2,6)	44	58
EuroSID	0,9 (1,9)	1,0 (2,5)	55	64

Table 2. Peak accelerations/roll-rates of the motion base in the experiments. The peak values are accompanied by the maximum linear velocity achieved (in brackets, m*s^{-1})

The movement of the motion base was recorded by using three markers firmly attached to it (in the plane that served as a bottom of the car interior) The peaks stated in Table 2 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 sensitive to filtering. Different filter may have led to slightly different peak values.

The experimental peak values corresponded well with the lower range of values obtained by means of accident reconstruction of approx. 30 rollover-cases in the project database and were thus realistic. Higher accelerations and/or roll rates would have been achievable, but not imposed because of safety reasons.

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 mode.

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 was 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 evaluation 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).

The motion capturing system records the positions of the markers in individual frames, velocity and acceleration data are computed as the first and second derivative, respectively. Thus, these data are sensitive to the filtering as well as to artifacts caused by the vibration of the sled, the movement of the markers on the skin etc.

SIMULATION

A multibody model of the sled has been developed in MADYMO 6.1 including the sled, the motion base and the seat. The main structures of the sled and motion base were represented by planes and ellipsoids; the seat geometry was modeled in detail by using facets. The seat model inclusive integrated belt system and their contact characteristics based on laboratory measurements were obtained from a car manufacturer. The sled was attached to the reference space and its motion was prescribed by using the acceleration data measured during the experiment. In this way the simulated movement was identical with the real one.

The simulation model was first validated by reproducing the measurements with the Hybrid III – the MADYMO Hybrid III model was positioned in the seat, the movement of the motion base was simulated and the measured and simulated response of the dummy was compared.

In the second step, the biofidelity of the MADYMO 50% Human Male Occupant was assessed by means of simulating the experiments with the volunteers. In order to facilitate the comparison between the measured and simulated response of the occupants the same set of markers was used in the simulation as in the experiment for the kinematical analysis.

Several pre-simulation runs were required for the positioning and belting of each occupant. These procedures were carried out in accordance with the MADYMO Manual. All computations were performed by using MADYMO 6.1.

RESULTS

EXPERIMENTS – TRANSLATIONAL MOVEMENT

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 showed the neck muscles (sternocleidomastoideus) with the onset at approx. 0.1 sec. A little bit slower reaction time has been found for the abdomen muscles and the upper leg muscles (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 Fig. 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 approx. 0.2sec there is no difference between the left and the right hand side of the neck musculature.

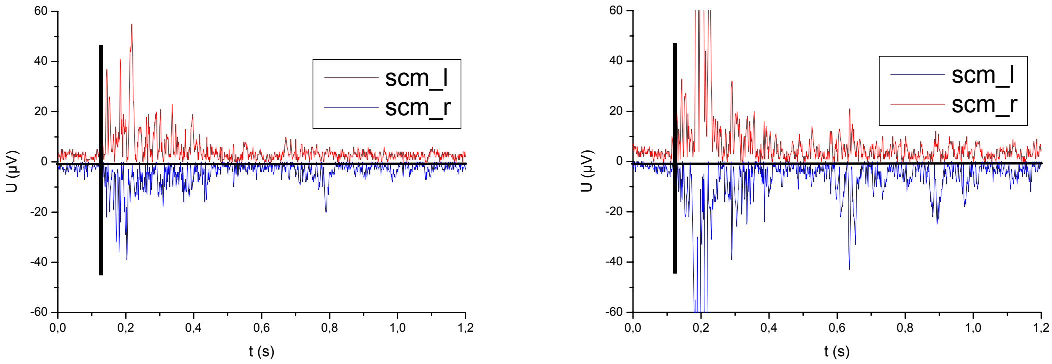
Also evident from Fig. 3 is a higher amount of muscle activity in the faster variant of the movement. Though it is impossible to quantify the force exerted by the muscles, the amount of muscle activity can be compared because the EMG signals were recorded in the same persons with exactly the same position of the electrodes. The 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.

The occupant kinematics is a very complex phenomenon. A simple comparison by means of 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 time points. In the following, only the most interesting screenshots are presented.

Only very little movement of the head and shoulder relative to the hip and chest occurs. Both dummies as well as (to a certain extent) volunteer 1 stayed with their trunk and head upright, volunteer 2 showed 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 correspond well with the deviations found in the EMG signals as discussed above.

Volunteer 1, slow (left) and fast (right) motion of the sled



Volunteer 2, slow (left) and fast (right) motion of the sled

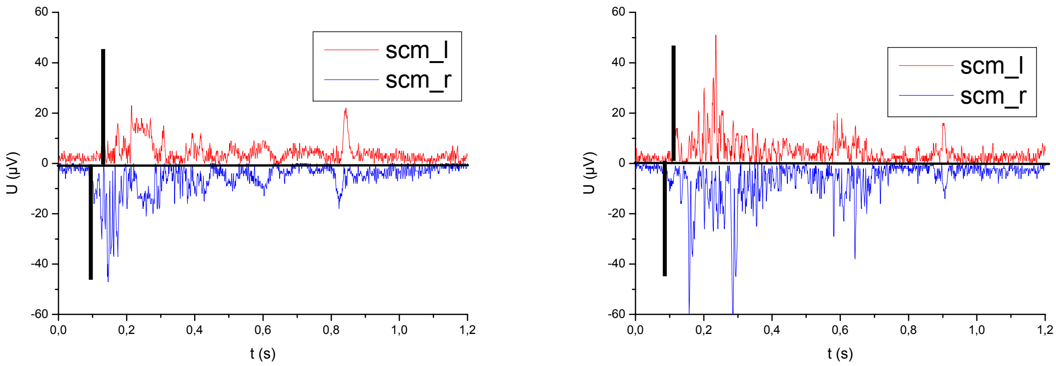


Fig. 3 - Comparison of the muscle activation on both sides of the human body – translational movement, m sternocleidomastiodeus left (light) and right (dark)

The dummy response met the 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 clearly in volunteer 2 would presumably become more apparent in both volunteers whereas the dummy response would stay the same. Because of safety reasons it was impossible to expose the volunteers to higher accelerations.

No 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.

EXPERIMENTS – ROTATIONAL MOVEMENT

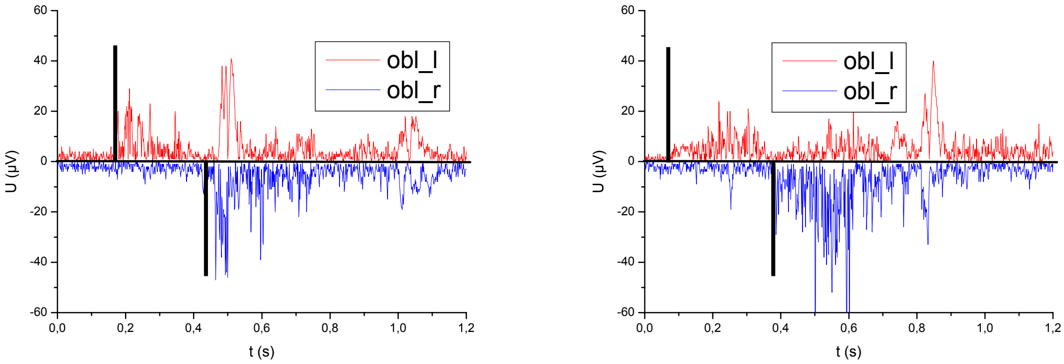
Similarly to the translational movement, all the selected muscles responded to the rotational motion of the sled. However, some differences in the response have been observed.

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 Fig. 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 side difference in the response of the abdominal muscles in the second volunteer. These reactions show possibly 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.

Volunteer 1, slow (left) and fast (right) motion of the sled



Volunteer 2, slow (left) and fast (right) motions of the sled

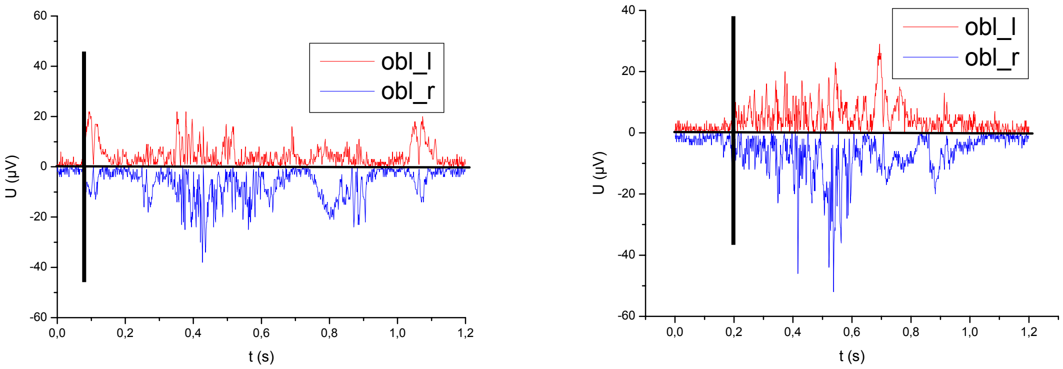


Fig. 4 - Comparison of the muscle activation on both sides of the human body – rotational movement, m. obliquus externus abdominis left (light) and right (dark)

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.

It should be noted that both subjects were not exposed to exactly the same motion of the sled because of the reproducibility issues as stated above. The found results thus may be influenced not only by individual reactions but also by the quality of the movement itself.

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

It is important to note that though the rotational movement of the motion base represented the first phase of other rollover type 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 identifiable relative movement in the torso or neck regions. As apparent from the figures, there are no differences between the two dummies.

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. Fig. 5 shows the comparison between the two movement types in volunteer 2.

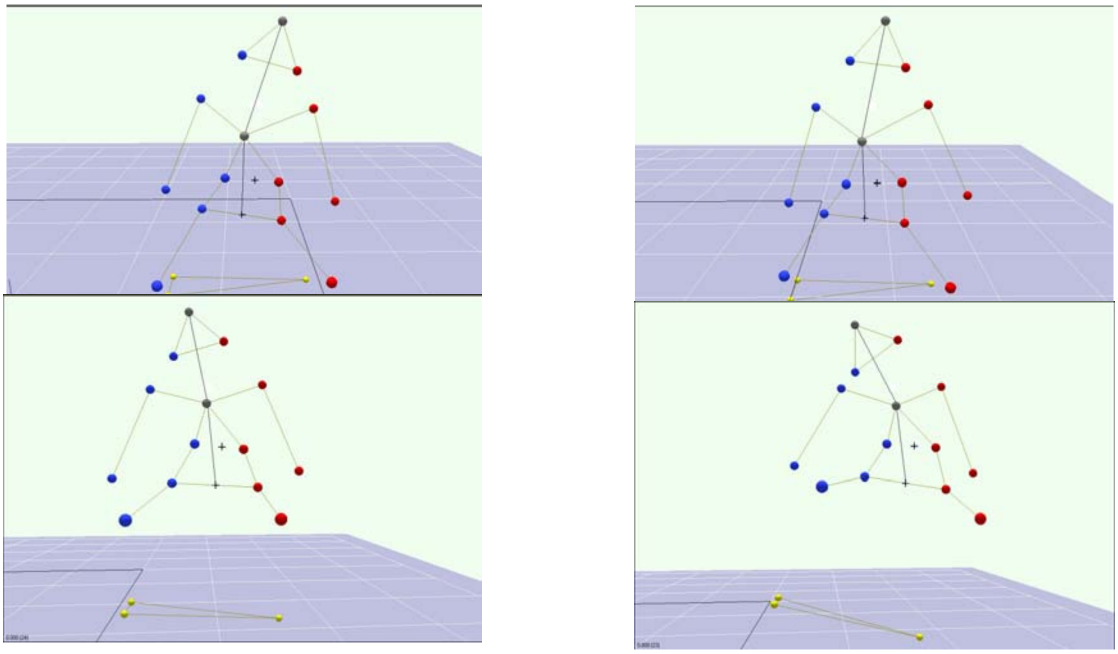


Fig. 5 - Bending in the torso and neck regions in volunteer 2 in the translational (up) and rotational (down) movement, the early (left) and late (right) phase, fast variant.

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

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.

Another difference is the rotation of the head of both volunteers about the longitudinal axes of their bodies. Both volunteers rotated the head relative to the rest of the body (clockwise from the top view) during the test. 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.

Fig. 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.

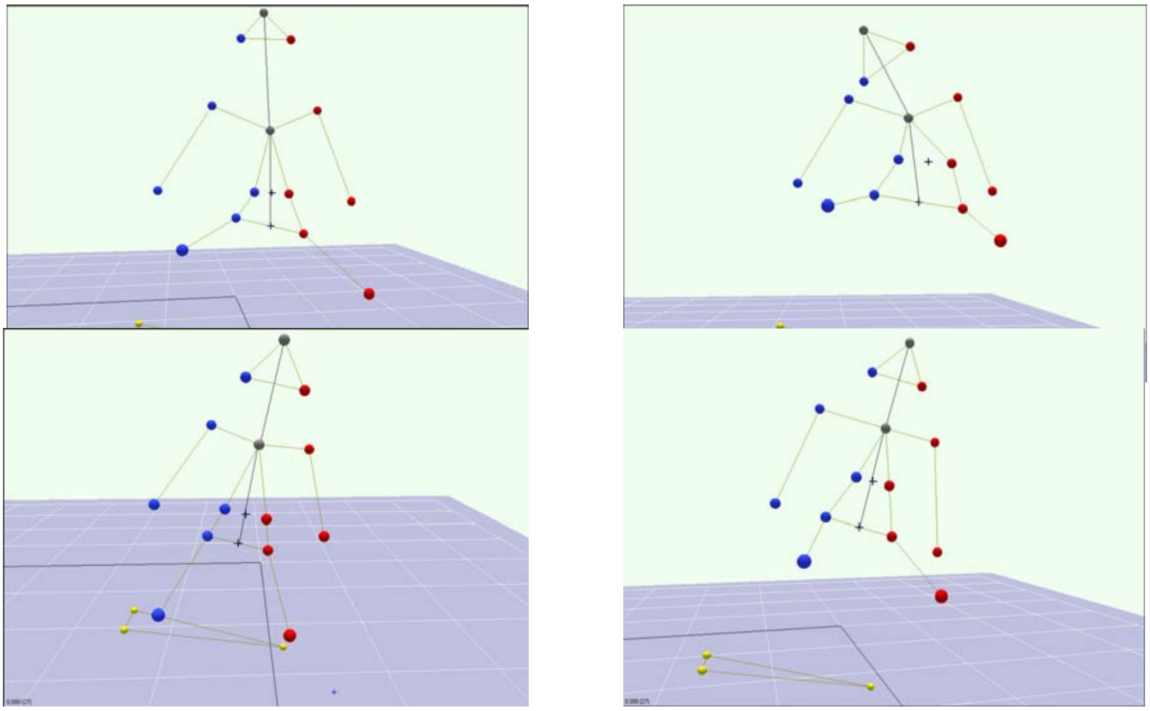


Fig. 6 - Difference in the lateral flexion of the head and upper torso of the volunteers and the dummies – late phase of the fast rotational movement. Top left volunteer1, top right volunteer 2, bottom left Hybrid III, bottom right EuroSID

SIMULATION – DUMMY MODEL

In the first step, the simulation model was validated by simulating the experiments with the HYBRID III. All test configurations with the dummy were simulated and the kinematics of the occupant were compared to the measurement results.

The dummy kinematics represented by the 3D positions of various markers showed the same development over time except for some minor differences caused by the fact that the belt was slightly tighter in the simulation than in the experiment (see Fig. 7). The overall (lack of) kinematical response to the loading of the dummy in the simulation corresponds well to the real measurement and thus the model could be regarded valid for the given situation.

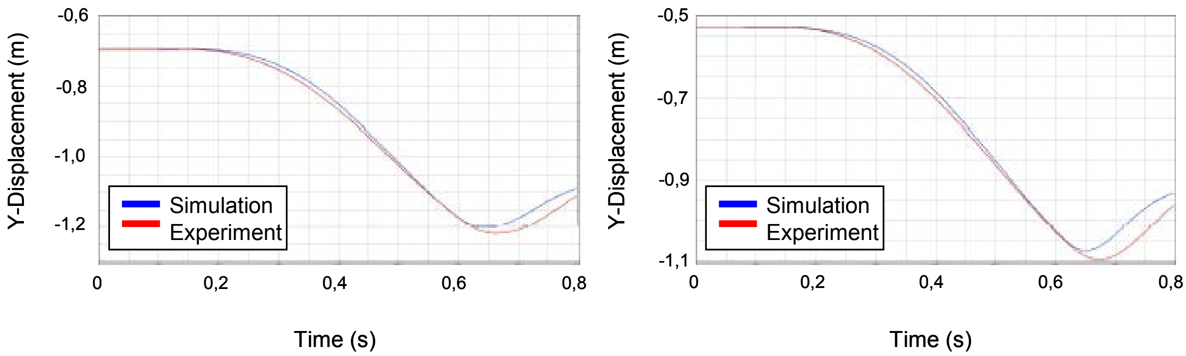


Fig. 7 - Comparison of a marker trajectory (head top) between the measurement and simulation

SIMULATION – HUMAN MODEL

The usability of the MADYMO 50% Human Male Occupant Model (and thus the potential of human models in general) to analyze rollover-like situations was investigated by means of simulation of the measurements with volunteers.

Whereas the differences between the experiment and the simulation are very small between the dummy and the dummy model, the deviations of the human model from the (both real and numerical) dummy kinematics are apparent. The hip and lower trunk regions are fixed by the mass of the occupant and the belt system, but there is a considerably higher amount of relative motion in the shoulder and neck regions of the human model. Please note that the occupant model is passive, the motion in the joints is held in the physiological range by implemented joint restraints. In general, the kinematics of the human model resembled to the one of volunteer 2 – the movement of the shoulder and head/neck had the same directions and order of magnitude, see Fig. 8.

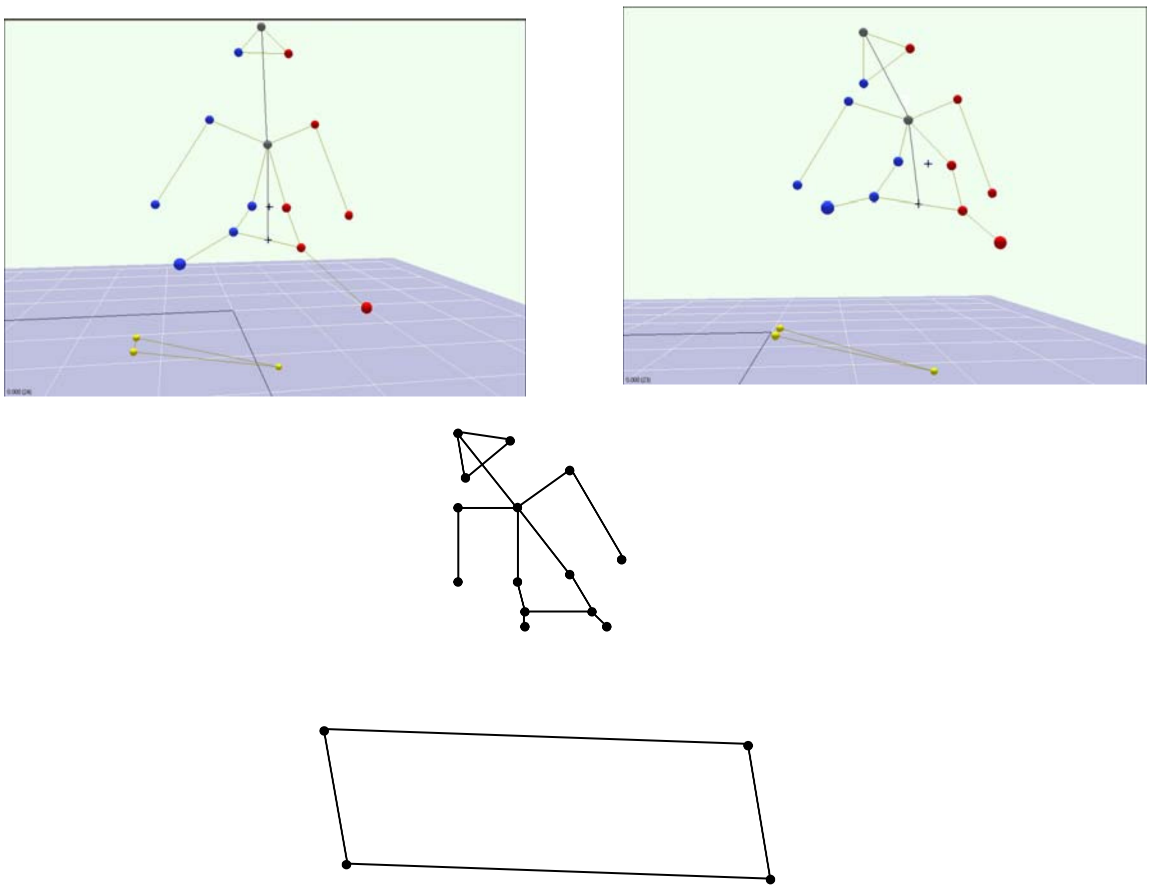


Fig. 8 - Difference in the lateral flexion of the head and upper torso of the volunteers and the human model – late phase of the fast rotational movement. Top left volunteer1, top right volunteer 2, bottom human model

DISCUSSION

The test setup simulating the first phase of a rollover accident exposed the occupant predominantly to lateral loading and therefore it could be assumed that the SID would perform better than the Hybrid III. However, our results do not confirm this hypothesis. There were no relevant differences found in the response of both dummies, both proved to be too stiff in the shoulder and neck region to allow for biofidelic kinematical response at this loading level.

Our results are in an agreement with the findings of Parenteau et al. (2002). They found similar differences between the Hybrid III dummy and human subject in low-level lateral impact situations in the head region.

The movements of the volunteers are predominantly influenced by the inertia of various body parts, but the effects of muscular actions proved to be relevant. Muscle activity was registered in all selected muscles, the reaction times of the muscles lie within the range measured in similar situations (Siegmund et al., 2003, Magnusson, et al., 1999). Higher acceleration levels resulted in higher EMG readings, because obviously more effort was needed to correct the body position by higher loads.

The results document that there is a high degree of interindividual variability among human subjects in their reaction to this type of loading. In accordance to findings of Vibert et al. (2001) we have identified two types of volunteer's response – the "stiff" and the "floppy" one. The stiff one shows collateral contraction of both left and right muscles that stabilize the torso and head/neck so only minor kinematical response is observable. The "floppy" type activates muscles mainly on the side opposite to the acceleration and shows wider range of motion in the shoulder and neck regions. The differences are apparent in the kinematics as well as in the EMG readings of the subjects.

It is important to note that though the magnitude of the kinematical response of the subjects varies, the direction of the relative body movements is the same. Field tests (Muggenthaler et al., 2005) have shown that the motion of the torso and head/neck of the dummy shows under certain circumstances similar amplitude but opposite direction in comparison to volunteers. Such differences are critical for the trimming of restraint systems where the position of the occupant must be taken into account. A false assumption of the occupant position for example after a pre-crash phase could lead to contra productive effects of restraint systems (OOP issues).

The simulation with the Hybrid III model reproduced the experiments very well. Because there was very little relative motion of various body parts, the movement of selected reference points (reflective markers on the dummy and virtual points defined in the same position in the simulation model) was compared in the inertial coordinate system. The simulation turned out to be almost the exact copy of the real measurement, the dummy movements as well as the dummy-seat-belt interaction worked out very well without any corrective measures.

The human model performed in the simulation significantly different from the dummy, the human model showed the same trends of occupant motion as the volunteers. The deviations of the human model motion with respect to the volunteer's kinematics can be attributed to the muscle activity that the human model is missing. Its joint properties are based on measurement on human subjects and the stiffness of the whole torso as well as head/neck and extremities joints is much lower in the physiological range of motion. For this reason, there is a certain slack apparent in the seating position of the human model and the kinematics during the lateral loading is the one of a completely passive human subject – the response is the result of solely the inertia and the joint constraints. Though the model seems to be more suitable to represent real occupants than any kind of hardware or numeric dummy, its lack of muscle activity leads inevitably to deviations. These are likely to decrease with higher loading levels, but in low-acceleration scenarios (pre-crash, rollover etc.) they play a significant role. Thus, though the human model seems to be the best tool at hand for the investigation of multidirectional crash situations, its needs further development is needed.

CONCLUSIONS

Both volunteers exerted in all tests active muscle forces; 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 response to various movements (rotational versus translational movement) is different. With increasing accelerations the EMG pattern does not change significantly, but the volume of measured muscle activity increases. Similarly, the occupant kinematics does not change substantially with increasing acceleration (i. e. the same relative motion of individual segments can be observed), but the trends become more apparent.

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.

There is a high degree of interindividual variability in the occupant kinematics.

Relevant differences were found between the kinematics of human subjects and both the Hybrid III and EuroSID dummies.

No preference with respect to usage of the Hybrid III or the EuroSID dummy in rollover scenarios can be recommended.

The numerical dummy models represent well the real dummy. The numerical MADYMO human model provides more biofidelic response; its kinematics is closer to the one of volunteers. However, for an exact reconstruction of the occupant response the muscle activity must be introduced in the model.

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