The influence of seatback reclination on body kinematics during low-speed frontal impact

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Abstract. Safety tests are generally performed in accordance with strict procedures that involve the use of a carefully positioned dummy. Safety tests are rarely conducted with the occupant being in a non-standard position. In real life driving, occupants, especially passengers, choose a more comfortable reclined position, and in such a case the body dynamics are different from those investigated in the standard safety test. Furthermore, with the rapid development of autonomous vehicles, which provide the possibility of the position of occupants being unrestricted, the investigation of “out of position” body kinetics is becoming more important. The presented study aimed to evaluate body dynamics with various seatback reclinations. Body dynamics were verified by simulating frontal impact on a sled system with the use of a standard 50 percentile Hybrid III dummy. Points of interest located on the dummies head, neck, pelvis, and legs were traced, which allowed its trajectory to be evaluated. Additionally, the maximal extrusion and the time of motion were evaluated. It was found that the maximal extrusion in the longitude direction is the same for semi and fully reclined seats. Furthermore, a reclined seat causes head rotation, which can result in neck injuries.

Keywords – dummy, accident, frontal impact

1. Introduction
The development of personal transport in the form of fully automated vehicles will mean that a minimal contribution from the driver is required. The driver will also become a passenger and will be able to travel in a more comfortable position (e.g. with a reclined seat). Therefore, there will be new configurations and seating positions that will differ from the solutions that are currently commonly used [1]. Initially, however, autonomous cars will use the current passenger and driver restraint systems. Most of the available results of the passive safety test were achieved in accordance with strictly defined standards in order to ensure the repeatability of the tests. Tests concerning the position of the passenger with the seat fully reclined are omitted in standard procedures.

It was found that a partially reclined seating position was the most comfortable for travelers, and also the most frequently chosen option [2]. However, different seat positions cause the unsatisfactory operation of the restraining system, which is designed for a specific position of a driver and passengers. In consequence, safety tests are performed in a range of defined operation regimes of the restrain system. The reclined seatback position has a significant impact on the performance of a seatbelt and airbag. The
The angle of the seat has an effect on pelvic movement in a crash, and may therefore increase the likelihood of serious injury [3, 4]. The most frequent cause of injury is the improper performance of a seatbelt caused by reclined seatback – i.e. submarining [5]. Submarining causes severe injuries of the lumbar spine and lumbar internal organs, which are often the reason for the many fatalities and permanent disabilities of passengers (including permanent lower body paralysis). Worldwide literature shows that submarining tests are mainly carried out in a numerical environment, and models that predict the risk of injury to reclined passengers are limited by a lack of sufficient reference data [3, 6]. The occurrence of the submarining phenomenon is influenced by body posture, gender, or BMI (body mass index) [7-9]. Apart from the seatback and belt position, the extrusion of the knee, the rotation of the torso and the difference of knee and head extrusion can be used for predicting the effect of submarining [10, 11]. Many researchers have investigated the severity of crashes for reclined seats, but there are very few papers that describe the body dynamics when the seat is reclined in various positions. Altered body dynamics can lead to the ineffective operation of the seatbelt, and in consequence, poor airbag performance [12]. Therefore, overall body dynamics should be considered. For example, submarining generates higher head impact energy due to the greater distance of the head to the airbag. Furthermore, it has been proven that the distance between the seat belt anchor and the hips corresponds to a reduction in head injuries and an increase of sternal deflection [13].

The study aimed to understand the influence of the sitting position on a reclined seat on the body dynamics during the sled test simulation of a frontal impact. For this reason, the trajectory of the head, neck, pelvis and legs is analysed with respect to various seatback angles. Additionally, the times after which individual parts of the body reacted to the impact pulse were also checked.

2. Materials and methods

The entire experiment was performed in the Laboratory of Vehicle Dynamics and Safety, which is located in the Research Complex GEO-3EM ENERGY ECOLOGY EDUCATION. The investigation consisted of verifying body dynamics during an out of position test. In this case, variable seat reclination was considered. The reclination ranged from the standard seatback angle, which is recognised as being comfortable – i.e., 110°, through 130°, and finally to a fully reclined seatback of 145°. The biomechanics of a crash were evaluated with the aid of a standard 50 percentile Hybrid III male ATD dummy. Each test was recorded using the Phantom VEO 410L high-speed camera. Every test was recorded at 5000 FPS with a maximum resolution of 800x1280. TEMA Automotive software was used for record analysis. High-speed record analysis consisted of tracking the points of interest located on the head, neck, hips and legs. The test station prepared for the experiments, with named points of interest, is shown in figure 1. The trajectory of the designated points on the dummy’s body was emphasized in the analysis. The reference point was fixed at the centre of the seat, and in consequence all trajectories were found for a movable reference point. Additionally, the dummy was equipped with an accelerometer in its head. The sample rate was set to 15kHz. The acceleration signals presented in the study are filtered with a CFC 1000 filter. Furthermore, in the body dynamics investigation, a backward head motion was expected, especially during the test with a reclinad seat. For this reason, only the X direction signal was taken into account, which is due to the fact that the resultant signal of the triaxial measurement would reverse the negative acceleration measured in the centre of the head.
3. Results
The result of the high-speed analysis shows that the body dynamics differ for different reclinations of the seat. As could be expected, the higher the reclination of the seat, the longer the distance the dummy needs to travel, which in turn makes the time of the motion longer. The path of the points and the time of the maximal extrusion is shown in figure 3. As can be seen, the paths of the markers are similar for the seatback angles of 110° and 130°. Moreover, despite the long-distance that the dummy needed to travel, the time did not differ significantly, which suggests a higher velocity of motion. On the other hand, for the seatback angle of 145°, the path was entirely different from the previous cases, and the duration of the motion was the longest. Additionally, the fully reclined seat caused a greater force to be applied on the dummies heals, which in turn prevented the forward motion of the ankles. In all repetitions of the test at fully reclined seat positions, the dummies shins were not thrusted forward.
Figure 3. The path of the points of interests and the time of maximal extrusion.

The comparison of the trajectory of points of interest located at the head and the neck are shown in figure 4. It appears that there was virtually no difference between the extrusion in the X direction for the seatback angles of 130° and 145°. However, when considering the overall trajectory of the points, it can be seen that the fully reclined seat provoked the longest path. Additionally, there was a significantly higher Z extrusion when compared to the previous tests.

At the seatback reclination of 110° and 130°, the head motion was rapidly reversed, which is manifested by a sharp peak in the trajectory lines. It is anticipated that such a tendency could have a beneficial influence on neck extension when compared with the test with a fully reclined seat. This, however, is impossible to prove in these studies due to the fact that the dummy used for this research was not equipped with appropriate measurement apparatus. In this study, only the trajectory of the neck points could be evaluated, and as expected, the trajectory of these points resembled the path of the head markers.

Figure 4. The trajectory of the points of interest located at the head and the neck of the dummy.

The crash pulse was unchanged throughout the test, but the seatback position caused different acceleration signals (figure 5). The standard seat back position provoked an intermediate value of head acceleration. For the seatback angle of 110°, the acceleration was 15g, whereas for the angle of 130° the acceleration was lower – approximately 11g. For the fully reclined seat, the acceleration reached 20g.
Figure 5. Head acceleration. ISO/TS 13499 description:
S1HEADCG00H3ACXA

The difference in acceleration signals can be explained on the basis of the trajectory of the points, which
were determined from the observer's perspective. At the angle of 110°, the head moved forward
immediately after a crash pulse, and there was a minimal negative acceleration in such a case. The head
rotation was relatively small (figure 6a), which caused an increase of the acceleration over time.
However, when the seat was further reclined, the head experienced backward motion, which is
manifested by the relatively long negative acceleration on the graph. Subsequently, the head was
reversed on a wider path, which in turn led to a wide and low acceleration signal (figure 6b). Finally,
when the seat was fully reclined, the head was moved backwards at the initial part of the crash pulse,
which is manifested by the negative value of acceleration. After that, the head suddenly moved in the
opposite direction, which caused the occurrence of a high peak of acceleration (figure 6c).

Figure 6. Trajectory of the points of interests on the head, as seen from the observer’s perspective:
(a) seatback angle of 110°; (b) seatback angle of 130°; (c) seatback angle of 145°.

The extrusion of the hips in the X and Z directions is shown in figure 7. As expected, displacement of
the hips was the shortest for the seat back angle of 110°. In this case, the maximum displacement in the
X direction reached approximately 6 cm. The seatback angle of 130° provoked the longest X extrusion,
and a similar Z extrusion to the seatback angle of 110°. The intermediate X displacement was found for
the seatback angle of 145°. The Z extrusion was initially negative in every case, which means that the
hips were pushed downwards against the seat cushion. Afterwards, the direction of motion was reversed.
The reversed motion is a consequence of the hips being stopped by the seat belt. The motion of the upper
body, and also the position of legs, forced the hip to move upwards. As can be seen in figure 6, the seat
back angle of 145° provoked the most significant Z extrusion of the hip. The submarining effect was
not observed in any of the tests.
Figure 7. The trajectory of the points of interest located on the hips.

The hip motion corresponds to the extrusion of the legs – in particular the X extrusion. The extrusion on the points located on the legs is shown in figure 8. Here, the seat back angle of 110° provoked the largest Z extrusion. In the case of both the 110° and 130° angles, the Z motion was similar, with the point being displaced being 7-8 cm. However, the Z displacement for the fully reclined seat was significantly lower when compared to the seatback positions with a smaller angle. This is due to the fact that the legs were not straightened in all of the repetitions of the test. The impact energy forced the heels to be pushed against the floor, and therefore the knees were not straightened and all the X motions for the knees were due to the whole body being in a forward motion.

The ankle motion for the seatback angles of 110° and 130° were similar. In both cases, the legs were fully extended, in turn causing the overall trajectory to be similar. However, for the fully reclined seat, the foot was not lifted, and the X motion originated from the hip forward movement.
Figure 8. Trajectory of the points of interest located on the leg: (a) lower thigh; (b) knee; (c) ankle.

The comparison of the motion of all the points of interest in the X and Z directions is shown in figure 9. It appears that extrusion in the X direction is virtually the same for when the seat is reclined by 130° and 145°. The extrusion of the points of interest at the standard seatback position (angle of 110°) was generally lower. Furthermore, and as expected, the most significant differences exist for the points that are distant from the hips.

The extrusion in the Z direction represents a different tendency. In general, the displacement measured for the tests with the seatback angles of 110° and 130° represents a similar tendency. However, considering the data spread, it can be concluded that those extrusions are different. For the test with the seatback angle of 145°, the displacement of the point of interest was entirely different. Unique in this case is the displacement of the points located on the neck. It appears that those points were moved in the Z-direction more than the dummy's head (in particular the point located on the jaw). This indicates significant neck tension and possible whiplash injuries. The Z extrusion of the points of interest located on the legs was the lowest for the fully reclined seat, because for this test the legs were not straightened.
Figure 9. Comparison of all the extrusion points of interest in the X and Z directions.

The seatback position not only had a significant impact on the trajectory of different parts of the dummies body, but also on the time that the specific point of interest began the motion. What is under consideration here is the time difference between the trolley motion and the reaction of the body. This time difference is shown in figure 10. It should be noted that the figure only contains the instance of motion of the points of interest, with no information regarding the direction of its trajectory. At the seatback angle of 110°, the difference in the time between the trolley starting and the dummy beginning its motion is the lowest when compared to all the other tests. In this test, the hips and the neck reacted at almost the same time. However, the reaction of the head was the longest, which is due to the neck flexibility and inertia forces. The similar difference in the time for the neck and the hips suggests that the lab belt and the chest belt caught the body in a similar instance, therefore minimizing the severity of the impact.

The seatback angle of 130° represents a greater delay of the body’s motion with regards to the trolley’s motion. In this case, similarly as for the seat back angle of 110°, the hips were the first to react to the pulse of the collision. The response time was comparable to the other tests, regardless of the angle of the seat. The delay of the subsequent points of interest was significantly higher. The neck and the lower portion of the head reacted after a longer time when compared with the top of the head. This is due to the backwards movement of the head, which exists for dummies sitting on a reclined seat. This indicates the occurrence of head roll, which may negatively affect the neck. In the case of the fully reclined seat, the reaction time was the longest – i.e. each point responded to the trolley’s motion after the longest time when compared to the previous tests. The point at the top of the head started its motion before the rest of the points located at the head.
4. Discussion
Reclined body dynamics in out of position testing is rarely investigated. Investigations regarding this matter are mostly of a numerical nature, where the greatest emphasis is given to the submarining effect and lumbar spine injuries.

The research presented in this paper found that the seat position significantly alters body kinematics. In consequence, injuries to occupants are also different for the same crash pulse. As was determined in [14], a greater load exists when the occupant is in a more reclined position. Moreover, the load is especially greater on the lower spine, and the likelihood of submarining increases. Additionally, during a frontal crash, the torso pitch is a result of the rotation of the pelvis [15]. Body kinematics that would cause minimal injuries occur when occupants move at a constant acceleration. This is usually achieved by active restrained systems [16, 17]. A reclined body posture unfavourably aligns body regions such as the pelvis, lumbar, spine and ribcage to existing restrain systems, in turn increasing the severity of the crash [18].

Papers describing body dynamics during vehicle crashes mainly focus on the standard position of the seat. Furthermore, the performance of standard ATD dummies is often supplemented with PMHS (post-mortem human surrogates). Research has shown that dummy models and human models give different results [19, 20]. The low-speed sled and low acceleration sled test with a volunteer, which focuses on body dynamics and the influence of pre-crash muscle tension, was described in [21] and [22]. However, again only one seatback position was considered, and therefore the results of only one seat position can be compared. Understandably, due to much lower acceleration than in our study, and the participation of live volunteers (representing much greater bioidely), the extrusion presented in our research is greater. However, taking into consideration the general displacement of all the points of interest that are present in both studies, it can be concluded that the results are comparable. Furthermore, it was found that the body dynamics of live occupants vary if the occupants are braced or relaxed before impact. Generally, a greater displacement of the occupants occurs when they are relaxed [23-25]. When comparing displacement data of the human body with that of an ATD dummy, it can be concluded that the dummy has a similar performance to a braced live occupant. The kinetic and kinematic response of ATDs does not entirely correspond to the performance of PMHSs, with discrepancies being visible for foot plate, seat back, steering column, and lap belt forces [26, 27].

The body kinetics during a crash test performed with a velocity of 40 km/h were investigated by Ash et al. [28]. The authors described the corridors of a body displaced in three dimensional environments. The position of the body, which was determined by the authors, is similar to that in [29]. However, the obtained results are 2 times smaller due to test speed being more than 2 times lower. In addition, the
general shape of the corridors was determined for the standard seat inclination of 110°. However, the results of the trajectory of the points for the tests of inclined seats extend beyond the corridors described in this paper.

5. Conclusion
The conducted research was carried out to evaluate the body kinematics for a passenger sitting on a seat that is reclined at different angles. It was found that there is a difference of body kinematics when sitting on a seat that is reclined. Forward motion (X direction) for the standard position of the seat provoked the lowest extrusion. For the intermediate seatback angle, as well as for the fully reclined seat, there was no difference in extrusion in the forward movement. An opposite tendency existed in the Z extrusion, where the fully reclined seat provoked the most significant motion of all the points of interest in this direction. It was also found that the duration of the total movement was different for all the seat positions. As expected, the hips were the first to react to the trolley’s motion. In the case of the standard seat position, the neck reacted almost instantly. Due to neck flexibility, the inertia forces caused the points at the head to react after a longer time. The head stayed in place when the torso and the neck moved. The points at the head then began to move. In all cases, rotation of the head was observed. The greater angle of the reclined seat, the greater the head rotation. For the fully reclined seat, the rotation was significant enough to cause neck injuries. Therefore, investigation of neck and whiplash injuries during a frontal crash can be seen to be justified. Furthermore, the greater the seatback angle, the greater the difference in time between the hip motion and the motion of the subsequent points of interest.

Acknowledgments
The research was carried out using the R&D infrastructure of the project Complex GEO-3EM ENERGY ECOLOGY EDUCATION.

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