Validation of the Causality of Influencing Seat Design Parameters, Identified by using Multivariate Analysis Methods, on the BioRID-II ATD Kinematics in Low-Speed Rear-End Impacts

Rolf Lechner, Ingmar Hailer, Stefan Horion, Hermann Steffan

Abstract An increased number of technological interfaces with the customers such as rear-seat-entertainment displays increase the weight that has to be carried by the front seat. Understanding and quantification of the influence of seat-design parameters in a rear-end impact enable design engineers to develop seats fulfilling requirements of test procedures with the aim to reduce the risk of an injury. The research objective is to verify the causality of influencing seat-design parameters of a seat identified by the use of multivariate-analysis-methods by reference to a front seat. The kinematic behavior of three seat-design parameters foam thickness and $_{K}x$ distance between the head restraint and the upper cross member of the seat-back were analyzed. It was shown that the results of multivariate-analysis-methods for the looked at seat-design parameters give a valid prediction of the influence on the kinematic behavior of a BioRID-II anthropometric test device due to a change in a seat-design parameter. It was concluded that these results help design engineers in an early stage of the development to improve the seat-design to reduce the risk of sustaining a whiplash associated disorder.

Keywords Whiplash, multivariate-analysis, rear impact, seat design, kinematic behavior.

I. INTRODUCTION

40 000 citizens in the EU still suffer long term whiplash associated disorder (WAD) annually with a socio-economic impact of approximately 10 billion € per year. These injuries account for approximately 70% of all injuries leading to disability suffered through vehicle crashes [1]. Various clinical symptoms such as neck stiffness, strain and headache are seen in car occupants. Different injury mechanisms of the cervical spine have been identified thus far, however, the extent to which a single mechanism of injury is responsible remains uncertain. The injury mechanisms, which were discussed and of which some are still being discussed, are: hyperextension, shearing between the vertebral bodies, violent pressure transient mechanism, facet impingement mechanism, upper neck tension mechanism and S-deformation [2-7].

Different active concepts were developed to reduce the risk of sustaining a whiplash disorder by reducing the score of injury criteria evaluated for the consumer regulation boards. Some of these can be classified in two general groups. The first group uses the principal of dissipating kinetic energy [8, 9] and the second group aims to reduce the backset during an early stage of the rear impact by using an active head restraint design [10, 11]. Reference [12] showed that advanced whiplash prevention systems and seats with a good rating in a consumer crash tests reduced the risk of sustaining a WAD.

To develop a passive seat-design concept with a good rating in a consumer crash tests, the influence of seat-design parameters on the kinematic behavior of an anthropometric test device (ATD) have to be understood. The influence on the kinematic behavior due to a change in a seat design parameter to reduce the risk of sustaining a WAD were looked at before by different researchers. The differences of the cited work in the applied method, used ATD and analyzed seat design parameters are shown below.

Reference [13] found that seat stiffness, the position of the head-restraint and frame strength relate to the risk of sustaining WAD evaluated with a Hybrid-III ATD. A strong seat frame reduces early seat-back rotation and reduces the gap between the head and the head restraint. A high and forward head restraint provides support of the head and neck. Reference [14] identified that the head to head restraint gap measured for the Hybrid-III ATD is mainly affected by the foam stiffness and lumbar type. An increase in lumbar support stiffness reduces

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torso penetration improving the maximum head-to-torso rotation angle. The penetration of the torso and the amount of time for lower torso rebound determine the torso angle at the time of maximum head-torso rotation. Whereas [15] showed that head rotation relative to the chest cannot simply be predicted based on seat-back recliner stiffness or head-restraint position. Optimal protection for an occupant should consider the design of the head restraint and seatback as a system. Reference [16] showed that the head rotation of the BioRID-II ATD was reduced by simultaneously restraining the head and thorax by higher strength seat components and an increase in the foam stiffness of the seatback cushion. Reference [17] analyzed for a BioRID-P3 ATD that the influence of foam properties of the seat were less influential than the gap between the head to the head restraint. Reference [18] analyzed the influence of seat-design parameters such as the recliner stiffness, head restraint height and backset on the different types of ATDs such as the BioRID-II, Hybrid III, RID-II, and THOR under rear impact condition. It was shown that the different ATDs responded different to a change in seat design parameters. Using a simplified simulation model [19, 20] proves that the structural characteristics of the seat plays a pivotal role rather than the head restraint with a good geometry. It was concluded that the seat-back has to be designed together with the head restraint to work effectively.

A general analysis of the impact of some influencing seat-design parameters on the kinematic behavior of the BioRID-II ATD, as a system, were shown by [21]. A multivariate-analysis-method approach was chosen evaluating tested seats by The European New Car Assessment Programme (Euro NCAP).

The objective of this study was to analyze the causality of the influencing seat-design parameters such as foam thickness, recliner stiffness and the $_kx$ distance between the head restraint and the upper part of the back-rest identified by [21]. A root cause analysis of the movement was conducted by objectifying the movement of the seat and the BioRID-II ATD individually and relative to each other. The influences of a change in the identified seat-design parameters on the kinematic behavior of a BioRID-II ATD were analyzed by comparing the kinematic behavior of a change in the parameter to the same seat without the change in the parameter. Via this method the causality of each factor was identified and the general applicability was proven.

II. METHODS

Prior to the dynamic test the seat position was adjusted according to the Euro NCAP testing protocol [22]. Once the seat position was adjusted the H-point, backset and height of the head restraint was measured using an H-point manikin (HPM) and a head restraint measuring device (HRMD). The rear impact collision was performed on an electric acceleration sled. The acceleration pulses used for the evaluation were the low, medium and high severity pulse defined by the Euro NCAP testing protocol [22]. The body-fixed and the inertia coordinate systems, as defined by the SAE J211 [23], were referred to in this paper and outlined by subscript k and subscript i respectively. The BioRID-II ATD was instrumented with acceleration sensors in $_kx$- and $_kz$-direction and a rotational sensor around the $_ky$-axis at the head, T1, T8 and Pelvis the C4 and the L1 were equipped with acceleration sensors in $_kx$- and $_kz$-direction at the positions shown in Figure 1. Each sensor recorded at a sampling frequency of 20 kHz.

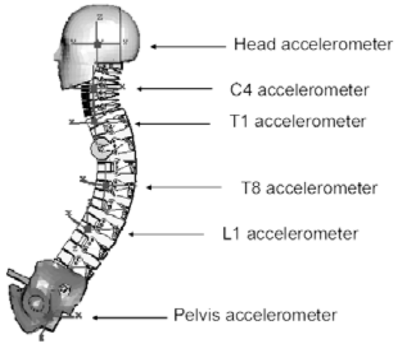

Figure 1 BioRID-II ATD sensor positions

In order to conduct a motion analysis of a seat from a recorded video the seat was equipped with MXT 5-point markers to measure the motion from a high speed video relative to a fixed point in the video. The measured positions on the seat were defined as shown in Figure 2. The high speed cameras recorded at a speed of 1000 frames per second.

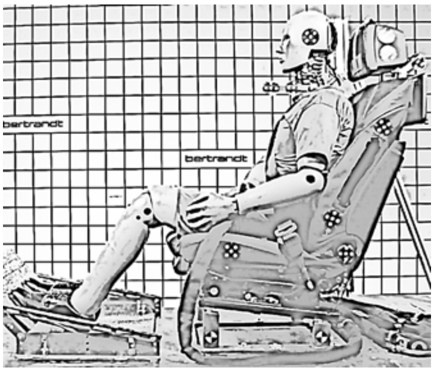

Figure 2 Test Setup including seat equipped with MXT 5-point marker

The MXT 5-point markers were attached to a rigid part of the seat frame or to a mounting part directly attached to the seat frame. The position and inclination of the MXT 5-point markers relative to a reference marker on the sled were measured from the video. In order to evaluate the kinematic performance of the BioRID-II ATD relative to the motion of the seat the body-fixed coordinate system had to be translated into the inertia coordinate system. This was done via a transformation matrix around the y-axis, ^{ki}A=[cos(α), 0, sin (α); 0, 1, 0; -sin(α), 0, cos(α)]. The initial position of the recliner was used as a reference point in order to conduct the comparisons between the different seat systems.

The following section describes the definition of the parameters, which were used for the evaluation:

The resultant velocity of each body region was obtained by calculating the square root sum of the square velocity in the $_kx$- and $_kz$-direction (see Formula 1). By integrating the resultant velocity a second time the resultant distance covered was obtained.

$$v_{res} = \sqrt{{}_k v_x^2 + {}_k v_z^2} \tag{1}$$

The acceleration term in the inertia coordinate system was obtained after these were transformed by multiplying the looked at term with a rotation matrix. Integrating the acceleration term twice the distance travelled in the inertia coordinate system was obtained and subsequently the trajectory of the measured body regions in the inertia coordinate system.

A statement on the change of linear and rotational momentum was obtained by analyzing the change in the resultant velocity, as the change of momentum behaves directly proportional to the mass times the change in velocity. The relative change in momentum caused by the impact of the head restraint with the head was evaluated by looking at the difference in the resultant velocity of the head and the head restraint (see Formula 2).

$$\Delta v = {}_k v_{Head} - {}_k v_{Head\ Restraint} \tag{2}$$

The specific accident capacity (SPUL) describes a mass free evaluation of the change in kinetic energy divided by the duration it is being applied (see Formula 3). The SPUL was calculated for each body region Head, C4, T1, T8, L1 and Pelvis.

$$SPUL = \frac{\Delta v(t)^2}{t} \tag{3}$$

where t is time (s), v is resultant velocity (m/s) and SPUL is specific accident capacity.

The total amount of rotation of each sensor and the rotation of each body region relative to the rotation of the upper part of the seat-back was evaluated. First the rotational speed measured by the rotational rate sensor was integrated with respect to time following on the relative rotation of each body region to the upper seat back rotation. The intrusion of each body region into the seatback was measured by evaluating Formula 4.

$${}_i x_{intr} = x_{BioRID-II\ KT}\left({}_i z\right) - x_{Ref\ Linie}\left({}_i z\right) \tag{4}$$

Where $_ix_{intr}$ is the intrusion of the looked at body region into the seat back, $x_{BioRID\text{-}II\ KT}$ is the $_ix$ position of the BioRID-II ATD as a function of $_iz$ of the BioRID-II ATD body region and $x_{Ref\ Linie}$ is the $_ix$ position of the reference line as a function of $_iz$. The reference line was determined by the recliner point and the head restraint rods exit points of the seat back. The ramping of each body region was determined by evaluating the individual body region movement along the upper seat back inclination. The neck injury criteria (NIC) and the neck protection criterion (N_{km}) were evaluated according to the Euro NCAP testing protocol [22].

The looked at seat was equipped with a crash-active-head-restraint (CAK) adjusting the position of the head restraint in $_{K}x$ direction by 50 mm. Relative to the reference seat the following modifications were considered. The increase in foam thickness was conducted by adding an additional 20 mm of the same foam on top of the seat back cushion underneath the leather cloth. Foam properties such as the stiffness or density of the foam were not changed. The $_{K}x$ distance of the head restraint to the upper backrest frame was reduced by not activating the CAK. The effective gap was therefore decreased by 50 mm. The kinematic influence was subsequently analyzed for each system and compared to the reference seat tested with the same acceleration pulse.

The results shown here were normalized relative to the maximum value of the reference seat and displayed in percentage with the maximum value of the reference seat being 100 %.

III. RESULTS

In the following section both parameters, foam thickness and $_{K}x$ distance of the head restraint to the upper backrest frame, are presented consecutively. First the increase of foam thickness is described which is followed by the $_{K}x$ distance between the head restraint and the upper cross member of the seat back. Each modification is compared to a reference seat without the described modification. For each parameter the static seating position is initially described and followed by the kinematic movement of the BioRID-II ATD relative to the seat. At last the resultant acceleration values, the forces and moments at the neck and the kinematic behavior of the BioRID-II ATD causing the obtained injury criteria are analyzed.

Increase of Foam Thickness

The following results describe the change in the kinematic behavior of a BioRID-II ATD during a low speed medium severity rear impact test on a seat with an increased foam thickness of 20 mm on the seat back. This is compared to a reference seat without the increased foam thickness on the seat back. Due to the increased foam the H-Point position of the BioRID-II ATD was placed 37 mm in $_{I}x$ further away and 25 mm in $_{I}z$ higher relative to the H-Point for the reference seat. Subsequently the distance between the head to the head restraint was increased by 13 mm.

Comparing the velocity in $_{I}x$-direction it is shown that the change of direction was spread over a longer time period. This showed that the pelvis was moving forward for a longer period of time compared to the head which lead to an increasing S-shape deformation of the neck. Considering the SPUL it was shown that the magnitude was reduced except for the head, which showed an increased SPUL during the forward motion of the head. The rotational velocity of the pelvis peaked earlier and was twice as high whereas the difference in the rotational velocity decreased towards the head. The flexion moment remained unchanged in magnitude and time despite of the change in foam thickness. The structure of the seat showed a higher amount of movement at the head restraint, which covered an increased total movement of 35 mm. The frequency of the seat remained unchanged at 6.17 Hz. The ramping at the pelvis was less compared to the reference seat, whereas the higher located body regions showed a significantly increasing amount of ramping up to +20% for the head. The penetration of pelvis into the seat back was 9 mm higher and got constantly reduced up to the T1, which showed a penetration of only 4 mm into the seat back. Due to the increase in foam thickness, the momentum induced into the seat was increased. This could be seen by the increased displacement of the head restraint. Due to the increased amount of rotation of the seat back the amount of ramping measured and the rotation of the body regions increased subsequently.

This described influence can be seen in the acceleration of the BioRID-II ATD, which was delayed in general with a fading prominence from the head to the pelvis. The head of the modified seat showed an increased and delayed $_{K}x$-acceleration of the head. The delay at the $_{K}x$-acceleration was also seen at the T1 position starting at 40 ms (see Figure 3).

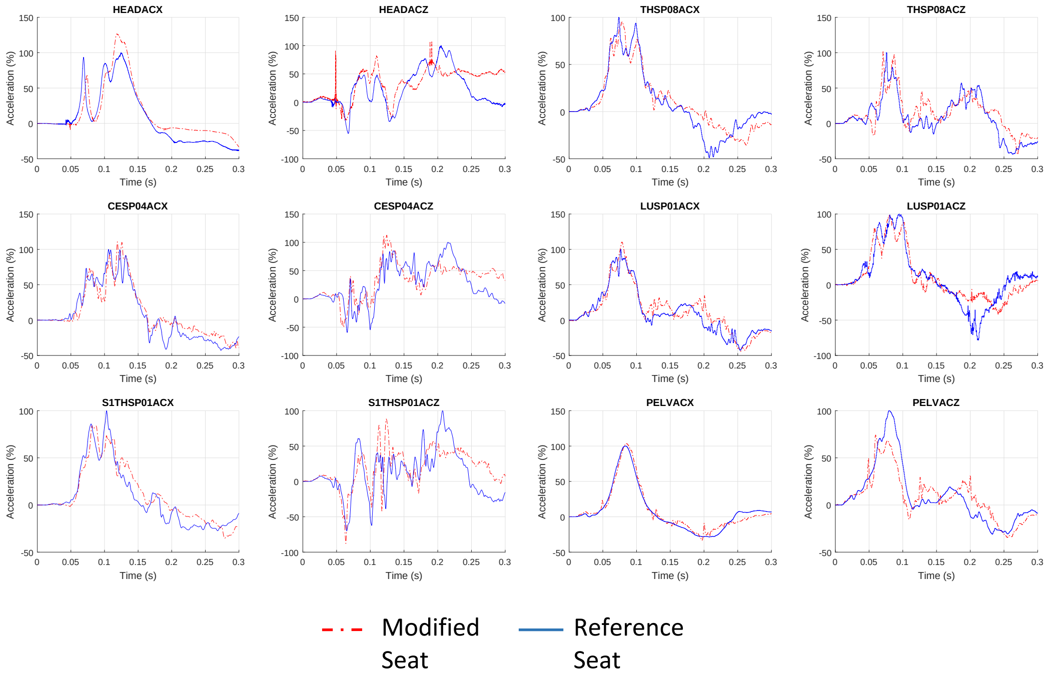

Figure 3 Acceleration behavior of the modified-seat compared to the reference-seat

The increased backset and further forward placed BioRID-II ATD position caused a higher change of resultant velocity of the head up to 3.5 m/s during the rearward motion. The difference in the resultant velocity was reduced towards the pelvis. Comparing the relative change in velocity between the head and the head restraint an increase in magnitude of factor two could be stated. Resulting from the different initial acceleration of the head and the T1 in ${}_{k}x$ direction a small increase of the NIC for the modified seat by 1 unit only and a delay of 6.5 ms was seen was measured. The NIC resulted in both cases due to a trough in the ${}_{k}x$ acceleration of the head down to 0.4 g for both seat designs after the first impact of the head with the head restraint. In consequence the peak acceleration of the head was increased and the minimum NIC reduced for the modified seat. The negative shear force for the upper and lower neck were increased and delayed due to the later impact of the head with the head restraint, whereas the tension force has not experienced a difference until the head got in contact with the head restraint. During the forward motion both shear and tension forces increased about 1.6 times in the magnitude of the reference seat, whereas the flexion moments slightly decreased (see Figure 4). Therefore, the N_{km} criteria experienced an increase in the flexion/anterior motion by 0.1 units during the forward movement of the body as the upper body got restrained by the seat belt. The flexion/posterior criteria peaked at the time of initial head impact with the head restraint and was significantly reduced due to the increase in foam thickness.

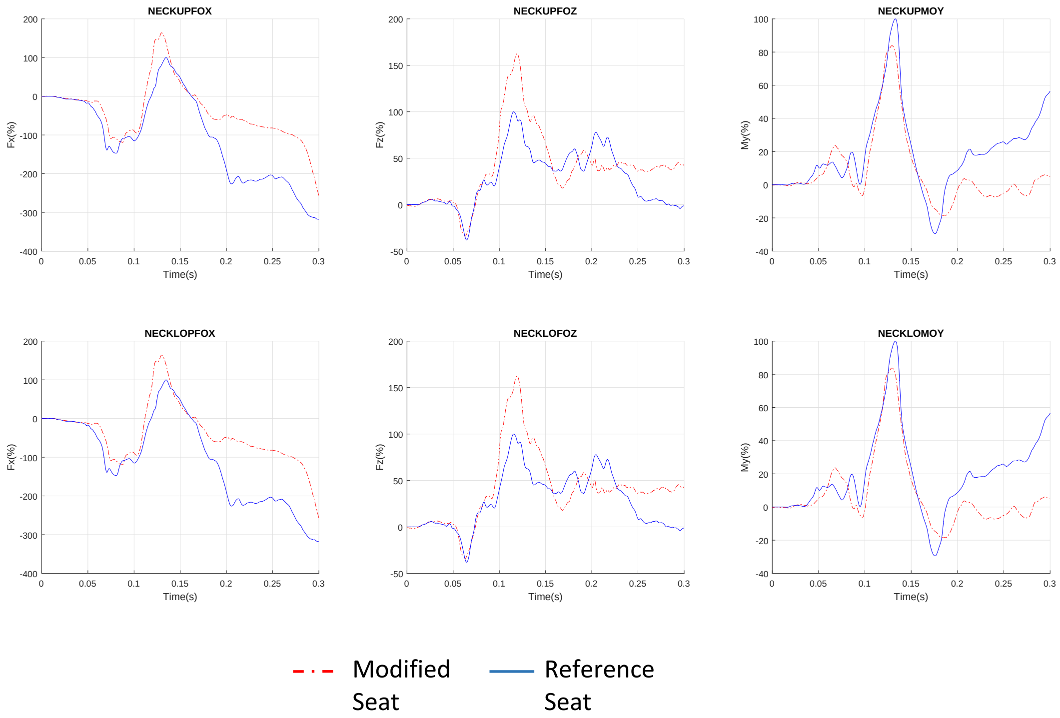

Figure 4 Forces and moments of the modified-seat compared to the reference-seat

$_{k}x$ distance between the head-restraint and the upper cross member of the seat back

The influence of a decrease in $_{k}x$ distance between the head restraint and seat back frame on the BioRID-II ATD kinematic behavior was analyzed in a low speed severity rear impact test. The initial position of the BioRID-II ATD was within the manufacturing tolerances for both seats. The $_{i}x$ position was moved by 4 mm forward and stayed on the same $_{i}z$ height. The gap between the head and the head restraint was increased by 7 mm. During the rear impact the contact point of the head restraint was moved rearward by 50 mm as the crash active head restraint was not activated for the modified seat.

The SPUL of the head was significantly delayed and increased for the modified seat to a higher maximum at 165 ms. This was due to the higher resultant velocity of the head by 1.3 m/s. As the velocity of T1 only slightly changed, the SPUL at the T1 sensor showed a minor and constant reduction. Due to the increased backset the rotation of the T1 showed an increase by a factor of two. The rotation of the body regions from the T8 to the pelvis did not show any major differences. The head restraint showed an increased displacement of 14 mm at a similar frequency of 6.8 Hz as the impact velocity of the head was increased. The head was able to move further rearward and therefore, caused an increase in the ramping of the head. The difference in the amount of ramping was constantly reduced towards the pelvis.

The described modification resulted in a delay of the head contact time by 39 ms and a subsequent increase in the peak $_{k}x$-acceleration of 5 g at the same time. From the T1 sensor to the pelvis the described delay was not seen. Due to the activation of the head restraint an acceleration of a factor of two to the modified seat after 34 ms at the head restraint was measured. The activation caused a turbulent increase of the $_{k}x$-acceleration from the T1 to the pelvis (see Figure 5).

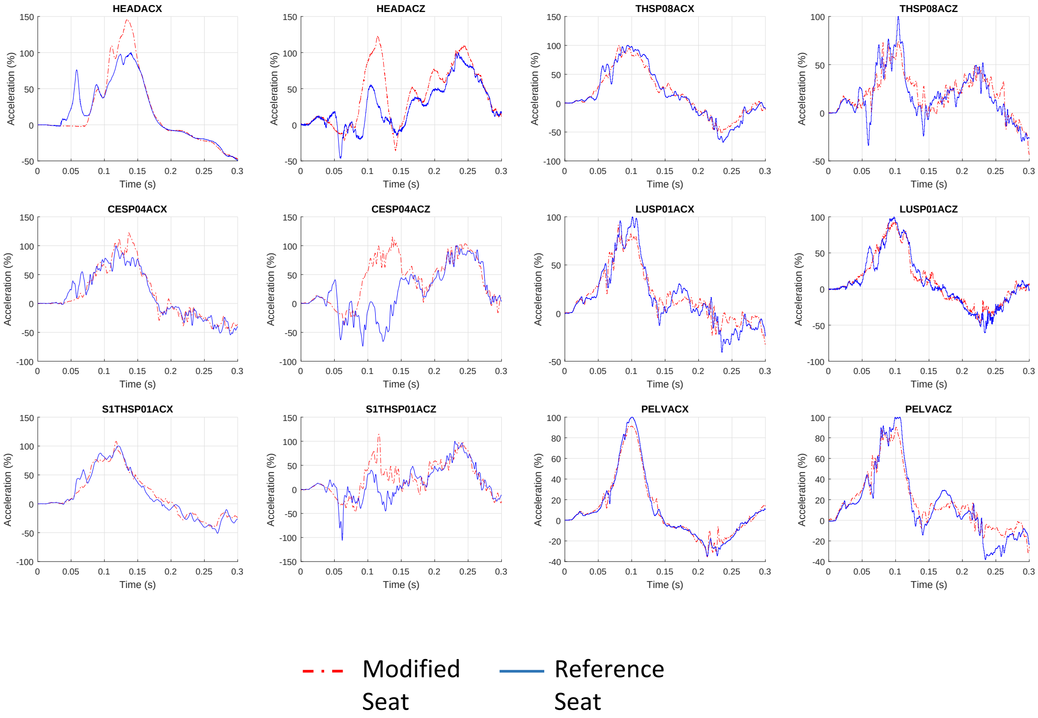

Figure 5 Acceleration behavior of the modified-seat compared to the reference-seat

The characteristic of the NIC significantly changed due to the modification as the reference seat showed two peaks at 68 ms and at 98 ms of the same magnitude, whereas the modified seat showed a single peak NIC of the same magnitude between the peaks mentioned before. Both peaks of the reference seat resulted from a trough in the ${}_k$x-acceleration of the head as it bounced off the head restraint, while the T1 ${}_k$x-acceleration noted showed a constant increase. The maximum NIC of the modified seat resulted in a constant increase of the T1 ${}_k$x acceleration and a delayed increase of the head ${}_k$x-acceleration.

The change in relative velocity of the head compared to the velocity of the head restraint showed that the reference seat initially experienced a negative velocity before the first contact of the head to the head restraint. Due to the longer unrestrained acceleration the relative velocity of the modified seat showed a higher and delayed maximum relative velocity of up to 1.9 m/s. The initial negative relative velocity was caused by a higher acceleration of the head restraint at the time the crash active head restraint was activated. Due to the later head impact of the head restraint in contrast to an equal behavior of the T1, the shear force response was delayed and rose to a higher level. The tension forces of the upper and lower neck were increased in magnitude as the reference seat dropped prior to the peak further as the head was restrained before the torso movement got restrained. The extension moments were reduced but the flexion moments during the forward movement increased by a factor of two instead (see Figure 6). These changes in the kinematic behavior readings resulted in a different N_{km}. The reference seat was defined by the extension/posterior movement with a peak at 110 ms, whereas the modified seat showed a maximum N_{km} defined by the flexion/anterior criteria at 144 ms.

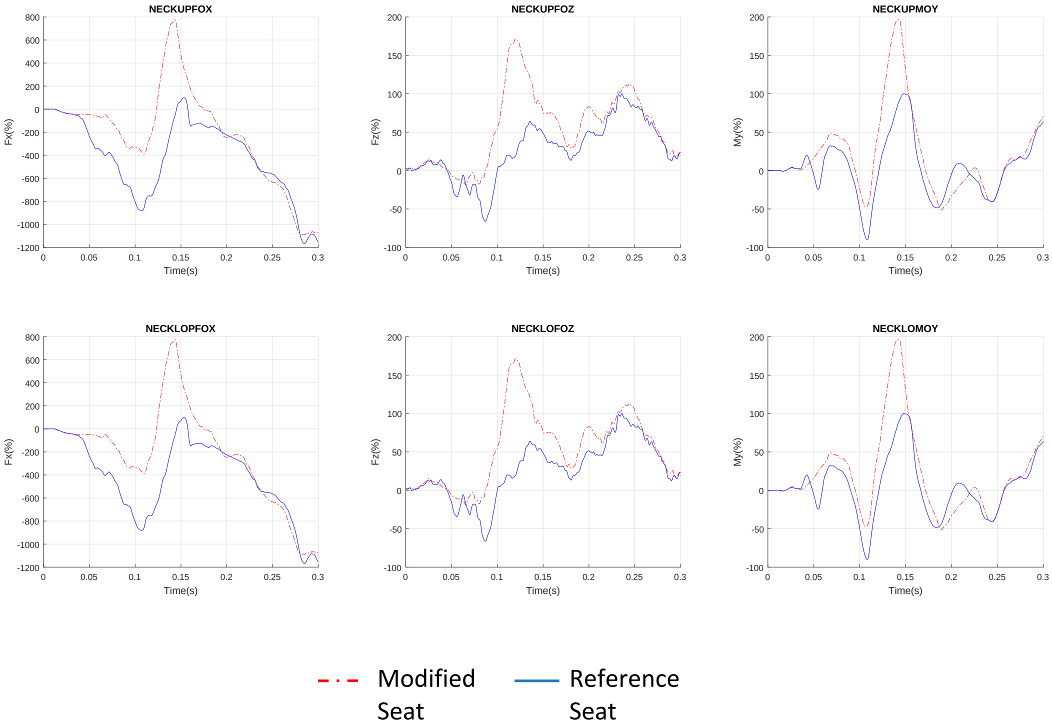

Figure 6 Forces and moments of the modified-seat compared to the reference-seat

IV. Discussion

The following section is structured in the following way. First the postulated factors describing the influences of the seat design parameters determined by [21] are stated. Following up on the results obtained in this study the postulated influences are discussed. Finally contributions by other authors are reflected to the obtained results if applicable.

First the influence of the foam thickness will be discussed. Reference [21] postulated the following factors including foam thickness: 1. An increase of foam thickness on the seat back together with a decrease of foam thickness on the head restraint and a decrease in seat back deflection would result in a decrease of the head contact time, the tension force, the rebound velocity, the neck shear force and the max flexion moment. 2. An increase in foam thickness together with an increase in foam thickness at the head restraint and the height of the backrest would increase the flexion moments. 3. An increase of the foam thickness at the seat back with a reduction of the seat back height and the seat back deflection would decrease the tension force and increase measures of T1. 4. An increase of foam thickness on the head restraint and on the seat back result in a decrease of the extension moments and the NIC and in an increase of the flexion moments.

This experiment showed that the NIC was slightly increased. The increase of foam thickness on the top of the seat back increased the delay from the pelvis to head and subsequently changed the timing of the ${}_{k}x$ acceleration relative to each other. Nevertheless, the peak acceleration of the head and the T1 acceleration in ${}_{k}x$ direction was reduced and significantly delayed. As this seat showed a sudden drop in the head ${}_{k}x$ acceleration after the initial impact the resulting NIC only showed a minor influence induced by the increased foam thickness on the back rest. Without the head bounce off the head restraint the NIC criteria would have decreased therefore significantly. The postulated reduction of the flexion moments were seen during the forward motion of the head restraint whereas the reduction of the tension force was not seen. The factor describing the reduction of the tension and shear force included an increase in the seat back deflection as well. Hence, it can be assumed that the postulated effect of the reduced shear and tension forces are mainly influenced by the seat back deflection rather than by the increase of foam thickness only.

Reference [17] found that foam properties only showed a limited amount of influence on the kinematic behavior and concluded that geometrical definitions of the head restraint showed the main influence. This study verified that the foam thickness significantly increases the amount of rotation throughout the BioRID-II ATD body regions and the subsequent injury risk criteria correlated with the kinematic response of the BioRID-II ATD. Reference [16] described the overall influence of the foam behavior during dynamic impact conditions. An increase in foam thickness reduced the maximum force reached for the same impact but also increased the gradient of the force over distance covered and delayed by the time of the maximum peak.

Next the decrease in the $_{K}x$ distance between the head restraint and the upper cross member of the seat back is discussed. By [21] the following statements were postulated: 1. A decrease in the distance between the head restraint and the upper cross member of the seat back together with an increase of the seat back deflection would cause an increase of the shear force, the lower neck extension moments and the upper neck flexion moments and result in a decrease of the lower neck flexion moments. 2. A decrease in the distance between the head restraint and the upper cross member of the seat back together with a decrease in the height of the backrest decreases the lower neck extension moments. 3. A decrease in the distance between the head restraint and the upper cross member of the seat back together with the decrease of the height of the backrest would increase the upper neck flexion moment, the shear force, the tension force and the lower neck extension moments. 4. A decrease in the distance between head restraint and the upper cross member of the seat back together with a decrease in height and an increase in foam thickness on top of the head restraint would cause an increase of the shear force, the tension force, the upper flexion moment, the lower extension moment and a decrease in the N_{km}.

The results show that most statements were found to apply as they were postulated except for the N_{km} and the lower neck moments. A comparison of the $N_{km,}$-values, reference seat and modified seat, showed a significant reduction of the extension/posterior movement of the neck. Nevertheless, the modification was as dominant that the SPUL of the head was able to build up to a point that the flexion/anterior movement criteria increased during the forward motion of the ATD until the total N_{km} showed a worse result. Overall it can be stated that the postulations by [21] were met as the extension/posterior N_{km} criteria was reduced. It becomes clear that a too significant change could cause a different kinematic behavior increasing the overall injury risk criteria again. The kinematic influences postulated for the lower neck moments were not identified in this test. This shows that spurious correlations could influence the statistical analysis due to parameters not included in the conducted analysis.

The test showed that the seat design parameters postulated by [21] cannot be separated and stand as its own as most factors included multiple seat design criteria. The factor always had to be looked at as a whole. Hence, most effects were proven as they were postulated by the multivariate-analysis-methods. Within this study only a change in a single criteria was analyzed. These changes subsequently caused multiple changes in the seat design system such as the increase of foam thickness which in consequence increased the backset.

V. CONCLUSIONS

In this study the causality of the influence of seat design parameters on the kinematic behavior of a BioRID-II ATD identified by the use of multivariate-analysis-methods were proven. In order to analyze the kinematic behavior of the BioRID-II ATD the trajectory of the body regions and of the seat were determined. The relative behavior was analyzed in detail focusing on the influence of the seat design on the kinematic behavior. Subsequently the causality was proven by altering a single identified seat design parameter and by objectifying the influence on kinematic behavior. Next the obtained results were compared to the postulated kinematic influence on the BioRID-II ATD. Overall it was shown that the method applied allows to give a proven prediction on the influence a changed seat design parameter on kinematic behavior. This knowledge can help guiding the seat design developer in order to improve the seat design as a system in an early stage of the development to reduce the risk of sustaining a WAD identified by the use of a BioRID-II ATD.

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