Effects of personal protective equipment worn by police officers on restraint system performance in frontal crash

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Abstract Police officers on duty wear personal protective equipment (PPE), typically consisting of a police belt with various accessories, a protective vest and a gun. In two frontal crash tests with belted midsize male ATDs in the front seats, the effect of PPE on occupant restraint performance was investigated. The ATDs were wearing regular clothing in the reference test and additional police PPE in the second test. While the ATD responses did not indicate an injury risk from the protective vest, the police belt with accessories prevented tight lap-belt fit, causing more forward displacement and higher leg loadings.

In a behavioural study, belt-wearing patterns were evaluated in a realistic setting. Thirty-six police officers were partnered as 18 teams to respond in a police car to a false alarm, both in a normal driving scenario and an emergency scenario. In 46% of cases the lap-belt was placed over or even above the police belt, increasing the risk for abdominal injury. In another 46% of cases the shoulder-belt was placed either too far outward or inward. Misplacements were mainly due to interference with items worn as part of the PPE. Careful positioning of the accessories would improve belt fit and should be promoted.

Keywords Occupant restraint, seat belt, police vehicle, crash test, behavioural study.

I. INTRODUCTION

Accidents involving police vehicles represent only a small proportion of all motor vehicle crashes. This is mainly due to the small proportion of these special vehicles in the entire motor vehicle fleet. However, their risk of being involved in a crash is much higher when responding to urgent calls and using emergency signals [1]. A NHTSA report from 2011 [2], based on FARS (Fatal Accident Reporting System) data of police officers killed in marked police vehicles between 1980 and 2008, found an increase in fatality numbers after 2000, with 36 occupants killed annually, on average. Of the total of 733 officers killed in police vehicles during the entire period of 28 years, 55% died in angle collisions and 27% in head-on collisions. Forty-two percent of the crashes occurred while using emergency signals. In 49% of cases with known belt use the officer was unbelted. The report noted that the percentage of belt use had decreased slightly during the period 2000–2008 in comparison to the 1990s.

In Canada, a study analysed approximately 7,000 motor vehicle crashes involving police cars of the Royal Canadian Mounted Police (RCMP), irrespective of the occurrence of personal injury [3]. The majority of the data derived from cases occurring during the period 2003–2010. Thirty-one percent of cases involved vehicles with their emergency signals activated, 38% marked vehicles with signals deactivated and 31% unmarked vehicles. In all, 2% of crashes resulted in injuries to a police officer and 2% resulted in injuries to the opponent. Ninety-one percent of the injured officers were classified as having sustained minor injuries and no officer fatality was reported. No data on belt usage were provided in the report. In all, 46% of crashes with documented collision type comprised side-swipe and rear-end collisions, whereas head-on collisions accounted for 17%. On an individual level, involved officers had, on average, nine years of service experience. Seventy-two percent of the officers were on duty at the time of the crash and thus presumably wearing their protective equipment. Of the involved officers on duty, 91% were on the first shift of the cycle.

The Swedish National Road and Transport Research Institute (VTI) conducted sled tests in 2005 [4] to simulate a frontal crash and conducted full-scale side crash tests in 2011 [5] using a trolley-mounted impact pole running into the side of a stationary passenger car. The tests were aimed at investigating whether personal protective equipment (PPE) worn by police officers would affect the performance of occupant restraint by the seat belt and

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side airbags under crash conditions. In the frontal impact simulation, Hybrid III midsize male ATDs were placed on the driver and passenger seats of the sled buck and belted with a regular three-point belt system incorporating a retractor-mounted pretensioner. In different combinations, they were wearing a protective vest and a so-called police belt with accessories like handcuffs, baton and a holster to accommodate the pistol. Although some biomechanical loadings were recorded, the focus was on the use of pressure-sensitive film that was placed on the hip, abdomen and chest areas in order to identify particular local loadings on these body regions during the interaction with the seat belt and the PPE. The results did not indicate an increased injury risk from the protective vest although a contact between the ATD's chin and chest was noted. The lap-belt routing was considered unsatisfactory as more belt slack was found when the ATD was wearing the police belt with accessories. Therefore, a higher risk of submarining was hypothesised. Contrary to the frontal tests, some of the side crash tests employed seat-mounted side airbags in order to identify any adverse effects in combination with the PPE worn by police officers. No major issues were found, but the pressure-sensitive film placed on the ATD indicated that hard objects worn on the hip, like the pistol in the hard-plastic holster, would exert localised high pressure on soft tissue or even on skeletal structures, particularly in the pelvic region, during both a frontal and a side crash.

In Germany, police are organised on a level of each of the 16 federal states. Accordingly, PPE and police vehicles are provided by the relevant federal state, also for local police forces. Typically, regular police patrols and responses to urgent calls are staffed by a team of two police officers. With regard to involvement in road traffic accidents or the number of police officers injured or killed as vehicle occupants, no official information is publicly available.

The police force in the state of Hesse introduced an altered protective vest for police officers in 2018. It features a sheet-metal inlay on the front and on the rear of the chest. In addition, the front inlay incorporates a so-called "blade catcher" on its neckline, which is a downward crease covered with thin padding (Fig. 1, right). In the case of a knife assault coming from the hip level of an opponent and being directed at the chin of the officer, it is intended to stop the blade or direct it to the side. Concerns were raised by police personnel that the "blade catcher" might present an injury risk to the neck and the head when officers as vehicle occupants become involved in a collision, particularly in a frontal crash. This led to a study to investigate whether PPE in general, as typically worn by German police officers on duty, would affect occupant restraint system performance in a frontal crash. Along with the protective vest, the police belt and attached accessories were also included in the study's investigation into crash safety (Fig. 1, left and centre).

Fig. 1. Protective vest and police belt with accessories and thigh holster with pistol (left, centre). Sheet-metal inlay with "blade catcher" (right).

II. METHODS

Aside from general considerations of the possible effects of PPE on crash safety, two full-scale crash tests were conducted aimed at determining the influence of PPE on the biomechanical loadings experienced by the driver and the front-seat passenger of a typical police car in a frontal collision.

In order to examine the use patterns of the seat-belt system, a behavioural study was conducted under controlled conditions with 18 teams of police officers. It focused on the main safety issues identified in the previous crash tests.

Crash tests

Two full-scale offset crash tests were conducted with minivan-style passenger cars (Opel/Vauxhall Zafira) at an impact speed of 57 kph. The car model was produced from 2005 to 2014 and was among those used as patrol cars in police service. The offset was 40%, with much of the impact energy being introduced to the driver-side vehicle front structure. The front-seat occupants were protected with driver and passenger frontal airbags, side airbags mounted in the seatbacks and curtain-style side airbags reaching from the first- to the second-seat row. The front seat-belt systems consisted of a three-point belt system with manual height adjustment of the D-ring, belt-force limiters on the retractor and pyrotechnic buckle pretensioners. The seats offered adjustment in the longitudinal and vertical directions, and for the inclination of the seatback and the seat basis, i.e. the seating surface, as well as head restraint height adjustment. The energy-absorbing steering column was adjustable in depth and height, i.e. the tilt angle.

Two Hybrid III midsize male ATDs were placed on the driver and passenger seats. Both seats were in the same position, with the height and seat basis adjustment down, the seatback at an angle of approx. 25° and the seat track set approx. one third of the full seat track range forward of the most rearward position to allow a comfortable posture for the driver. The ATD position was documented by measurement of characteristic landmarks relative to the vehicle environment (Appendix I). The steering column was set at mid-position and the seat-belt D-rings in the uppermost notch to allow the shoulder-belt to run across the mid-portion of the shoulder. The front doors were removed and replaced with horizontal steel bars to improve view of the ATD kinematics during the crash.

The driver ATD featured standard instrumentation in the head, chest, pelvis and femurs plus force and moment measuring in the upper neck and in the upper and lower tibia. Pelvic load sensors to measure iliac forces were not installed. The passenger ATD remained uninstrumented. Standard load cells and transducers were used for measuring belt forces for the driver on the lap-belt inboard and outboard side as well as on the shoulder-belt and acceleration on the vehicle tunnel (Endevco 7267A-1500). Data were filtered according to SAE J 211 and EuroNCAP requirements [6]. ATD kinematics were assessed on the basis of visual inspection of the crash test videos taken from identical perspectives in both tests.

In the first test, both ATDs were wearing a regular police uniform over the tight-fitting clothing required in standard crash tests. In the second test, the protective vest and the police belt and holster were added. A telescoping baton, handcuffs, a small flashlight and a can of pepper spray were attached to the belt and the holster, which held a training pistol worn on the lower right hip. A hand-held radio device was attached with a clip to the left shoulder portion of the protective vest. Due to the additional equipment and the seat adjustment remaining unchanged, the ATDs were sitting more upright in their seats in the second test, with the upper torso approx. 20 mm (passenger) and 50 mm (driver) more forward and the knees approx. 10 mm closer to the instrument panel (Appendix I). The protective equipment added more than 8 kg of weight to the ATD mass.

Foam neck shields were installed on both ATDs to provide for a more realistic neck circumference. In the second test, the neck and lower chin area were covered with a thin layer of cellulose tissue and colour markings were applied to the top edge of the protective vest in order to identify possible contact between the ATD's chin and neck and the "blade catcher".

Behavioural study

Eighteen teams, each consisting of two recruits, here referred to as "officers" or "participants", were formed randomly for the study. These were students in the last semester of the three-year program at University of Applied Sciences for Police and Administration for Hesse (HOEMS), a police academy in the state of Hesse that trains and educates students for police duty. All of them had completed driver trainings during the second semester as part of their regular training plan.

Two identical police cars were available for this part of the study, the vehicle model being the successor generation to the one used in the previous crash tests. In contrast to the crash-tested vehicles, this model features double belt pretensioners, one on the retractor and one on the outboard anchor of each front seat. In both test vehicles the adjustable steering column and the seat-belt height adjuster were set at their mid-position. The driver and passenger seats were placed in a position – approximately one-third of the full seat track range forward of the most rearward position – which was deemed comfortable for a driver who was 180 cm tall. The seat height and seat basis adjustments were fully down. All default positions were marked with small pieces of adhesive tape.

For the study, each participant appeared in uniform and with his or her PPE, consisting of their protective vest and police belt, holster and pistol and standard accessories. These items were arranged on the uniform according to the officers' personal preferences and some even carried complementary accessories, like tourniquets. The teams were asked to show up at a given time at the test site, which was set up on the HOEMS university campus. There, measurements were taken of each participant's total height, leg length (crotch height as a proxy, with boots worn) and arm span when stretched out horizontally. Body weight was not recorded due to privacy considerations, but marked obesity or underweight was not observed among the participants due to the physical requirements for police service.

Each team was informed that the alleged background of the study was an investigation into the ergonomics of police vehicles. No reference was made to the main point of interest, i.e. the placement of the seat belt by the participant. This was omitted in order to prevent unnatural care being taken by the participants when putting on the seat belt. After that, each team received a task, in writing, describing one of the following scenarios:

- "Patrol scenario": you as a team are dispatched to a minor road traffic accident, with no injuries, some eight kilometers away. Get into the police car and start the drive. Maintain radio traffic with the dispatcher while travelling. There will be a third person in the vehicle, sitting on the back seat, for monitoring purposes. Your performance will not be rated in any way and the results will not be linked to you as an individual.
- "Emergency scenario": you as a team are dispatched to a severe road traffic accident, with imminent risk of death for victims, some eight kilometers away. Get into the police car and start the drive using emergency signals. Maintain radio traffic with the dispatcher while travelling. There will be a third person in the vehicle, sitting on the back seat, for monitoring purposes. Your performance will not be rated in any way and the results will not be linked to you as an individual.

Directly after reading the instructions, the study coordinator assigned one person of the team as the driver and the other as the passenger, i.e. team partner on the passenger seat.

The team then got into the police car, while maintaining radio communication with the dispatcher, in this case the study coordinator, and drove off. Shortly after that, the study assistant on the back seat told the team to slow down, if necessary, complete one lap of the campus and return to the start point. The study assistant made notes as to whether the participants fastened their seat belts before starting, during the first phase of taking off, or did not use their seat belt at all.

Upon arrival at the start point, the team was asked to remain seated and photos were taken from standard camera perspectives to document the seat and steering column positions, belt height adjustment and the position of the lap- and shoulder-belts on the hip and over the chest. Even then, the participants received no further information about the research background and were sent back to their classroom. The study assistant then documented all positions and how the seat belts had been worn on a form sheet and put the seat, steering column and height adjuster back in their default positions.

After the last of the 18 teams had completed the first round, the teams were asked to return to the test site separately and in the same order as previously. This time, each team received the written instructions describing the other scenario from that they had received in the first round, the roles of the driver and passenger were switched, and they were asked to drive a second round on the test course. Documentation was identical to that recorded during the first rounds of driving. Care was taken to ensure that there was as little contact as possible between different teams at the test site. All tests were conducted on one single day.

The tests received approval from HOEMS management and the participants gave consent to the use of their anonymous test data.

Assessment of the seat-belt position and routing on the body was done mostly on a qualitative basis because of the large variety of individuals' statures and number and position of accessories worn on their police belts and the protective vests. Two experts with a background in occupant safety research evaluated the photographs taken of the participants in the vehicle independently and coded the shoulder-belt and lap-belt positions according to three categories each.

The position of the shoulder-belt over the shoulder flap of the protective vest was assigned to one of the following three categories (Fig. 2).

- “Inward position”: shoulder-belt partially or completely over the “blade catcher” on the neckline of the vest.
- “Centre position”: shoulder-belt completely on the shoulder strap of the vest or slightly towards the arm.
- “Outward position”: distance between shoulder-belt and “blade catcher” 60 mm or more, equal to more than 125% of belt webbing width.

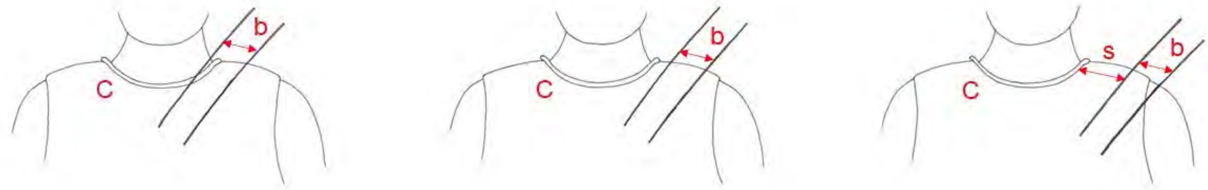

Fig. 2. Schematic representation of categories to assess shoulder-belt routing: “inward position” with belt webbing over “blade catcher” C (left), “centre position” with belt webbing on shoulder strap of vest (centre), “outward position” with distance s between shoulder-belt and “blade catcher” 60 mm or more (equal to more than 125% of belt webbing width b) (right).

The position and routing of the lap-belt was assigned to one of the following three categories (Fig. 3).

- “Below police belt”: lap-belt at least partially below police belt and not across more than one accessory item worn on front of police belt.
- “Over/across police belt”: lap-belt routed over or across more than one accessory item on front of police belt.
- “Above police belt”: lap-belt webbing routed above police belt and accessories with a distance of less than half of lap-belt width to lower edge of protective vest.

Items worn outside of the imaginary centre lines of the thighs, e.g. a pistol, and very soft items, e.g. protective gloves, were ignored in the classification of lap-belt routing.

Fig. 3. Schematic representation of categories for lap-belt routing: “below police belt” (left), “over/across police belt” (centre) and “above police belt” (right). Imaginary centre lines of thighs indicated by dash-dotted lines.

Regarding the variables of belt position, differences in frequency were determined for preferable positions (i.e. the centre position for the shoulder-belt, and the position below the police belt for the lap-belt, respectively) versus the unfavourable positions (i.e. the inward and outward position, and the position over and above the police belt, respectively). For a more detailed analysis of the influence of participant total height, three categories were defined: participants shorter than 175 cm, those measuring 175–184 cm and those 185 cm and taller.

Differences of values of dichotomous variables were tested for significance using the Chi-square test. Statistical significance was assumed at a p-level of 0.05, otherwise the difference was considered non-significant.

III. RESULTS

Crash tests

The two crash tests showed very similar behaviour of the vehicles (curb mass 1,500 kg) upon impact, in terms of resulting acceleration, energy dissipation by the vehicle structure and rebound from the barrier (Fig. 4). The offset crash produced a peak resulting acceleration of 42 g on the tunnel and a maximum deformation with emphasis on the left portion of the vehicle front that just maintained the structural integrity of the occupant compartment (Fig. 5). The differences in occupant kinematics and measured loadings can therefore be associated mainly with differences in the initial ATD positions and the effects of the protective equipment on occupant restraint performance (first test without PPE, second test with PPE).

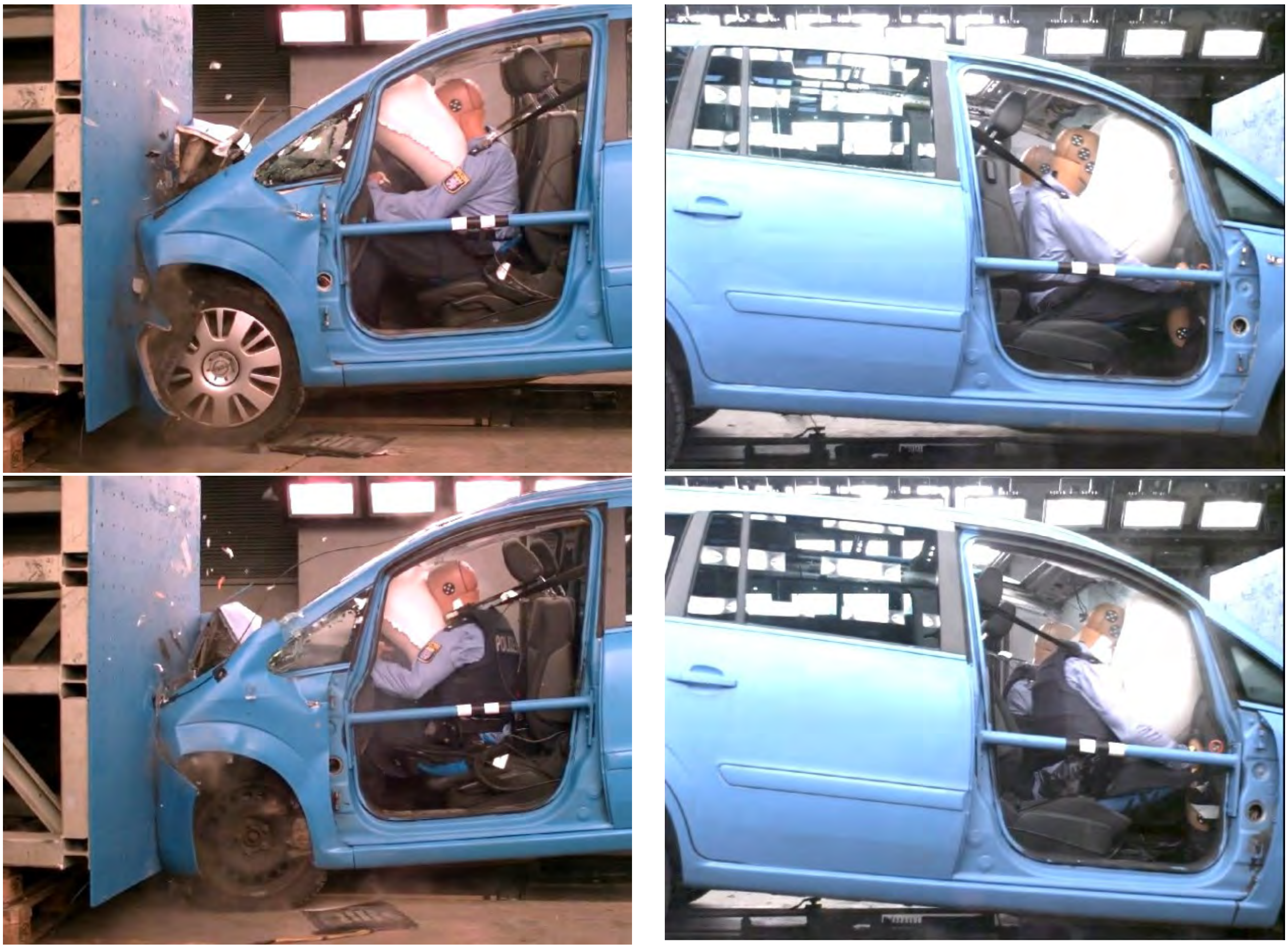

Fig. 4. Driver without PPE (upper left) and with PPE (lower left) and passenger without PPE (upper right) and with PPE (lower right), at time of respective maximum pelvis excursion.

During preparation for the test, the shoulder-belt could be positioned without problems over the ATD's shoulder and the protective vest, respectively. Routing of the lap-belt for the second test proved difficult. It was placed below the police belt to prevent sliding in the abdominal area during forward movement of the ATD in the crash. However, fitting the lap-belt tightly over the hip before the test was hampered by accessories attached to the police belt, like the baton and the pistol in its holster.

The seat-belt pretensioners and frontal airbags fired at 15 msec after first contact with the barrier in both tests. While the onsets of the shoulder-belt force for the driver occurred nearly at the same time, the force onset of the lap-belt was delayed by some 10 msec in the second test with the ATD wearing PPE, likely due to more belt slack in the hip area. Force limitation on the shoulder-belt of the driver took place at approx. 4.7 kN in both tests, resulting in a force plateau lasting for approx. 35 msec during driver ride-down (Fig. 5).

The driver demonstrated more pelvic forward excursion in the second test with PPE, causing more intense contact of the knees with the lower instrument panel and higher loadings on the lower extremities (Fig. 5). The Tibia Index values measured on the upper and lower tibia of the left and right driver legs remained below the

Euro NCAP threshold value of 1.3 (for lower performance) [7], but showed higher peak values in the right lower tibia in the second test with PPE (1.1 vs. 0.9) (Table A-II, Appendix 4). Also, femur forces were higher in comparison to the first crash test without PPE (left femur: 2.40 kN vs. 1.38 kN; right femur: 5.66 kN vs. 3.49 kN). Probably as a result of that, pelvic rotation about the vertical axis was more pronounced in the second test. While the femur compression values remained safely below the threshold value of 9.07 kN (lower performance limit in Euro NCAP [7]) the resultant 3 msec acceleration in the pelvis was quite high, with 65 g recorded in both tests (Fig. 6).

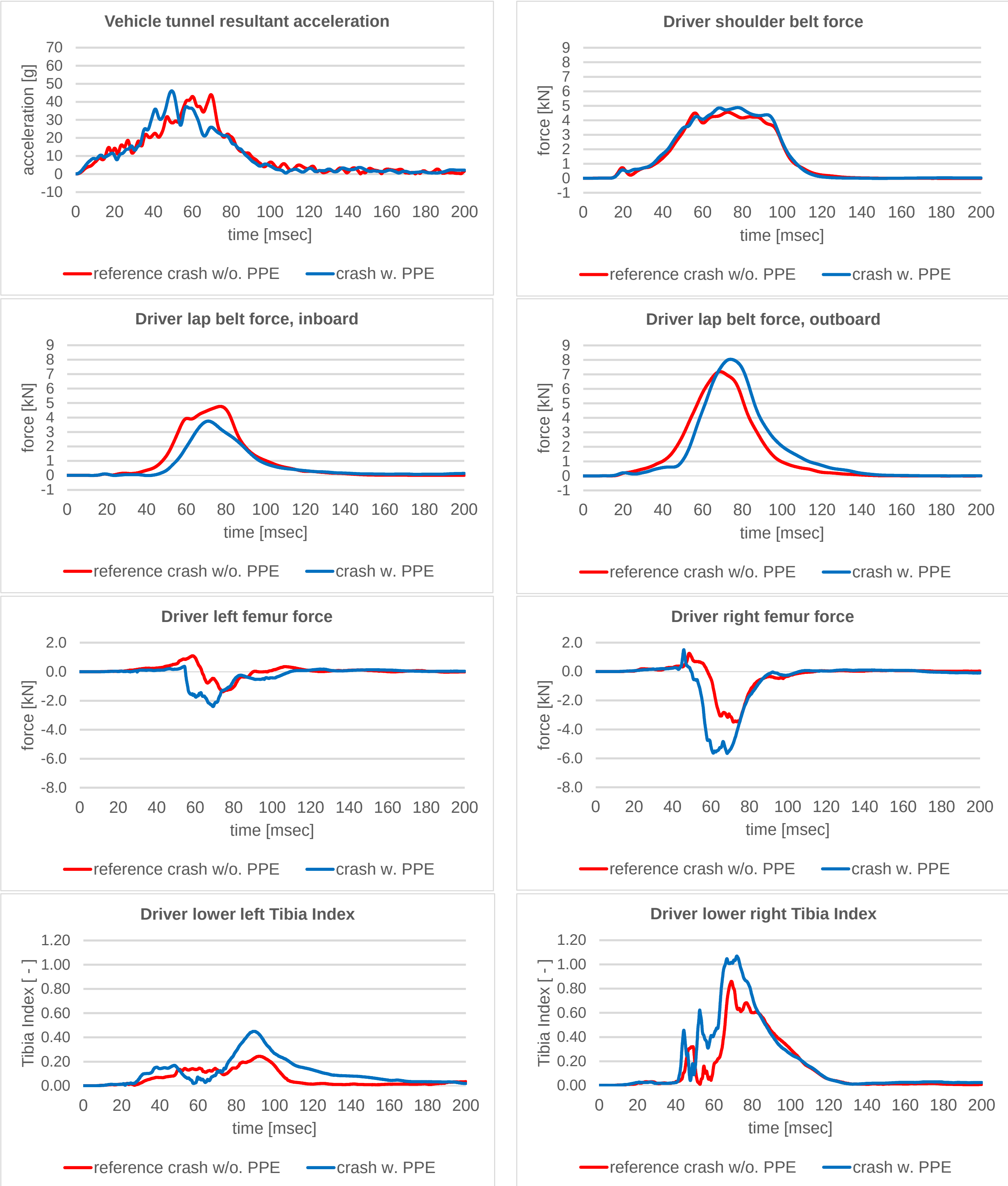

Fig. 5. Comparison of driver loadings in first crash test (reference, without PPE) and second crash test (with PPE), respectively. Vehicle acceleration and shoulder-belt force (first row), lap-belt forces, measured on buckle side and on anchor side (second row), femur forces (third row) and Tibia Index (fourth row).

In the thorax, the measured sternum deflection was lower in the second test with protective equipment than in the reference test (with PPE: 37 mm; without PPE: 44 mm), remaining clearly below the Euro NCAP lower performance limit of 60 mm (Fig. 6).

Neck loadings measured on the upper neck of the driver ATD differed slightly between the tests in character and peak values, but remained below the higher performance limits for neck shear and tension force and extension bending moment in Euro NCAP [7] (Fig. 6 and Fig. A-2, Appendix A-II; Table A-II, Appendix IV).

Resultant head acceleration curves for the driver demonstrated different characteristics and 3 msec peak values between the tests. In the second test with PPE, head acceleration started earlier but resulted in lower overall head loading in comparison to the first test (with PPE: 43 g, HIC 15: 178; without PPE: 55 g, HIC 15: 317). Evaluation of the crash videos shows that this effect is probably related to the fact that the ATD with PPE was sitting slightly more forward in its seat and that contact with the driver airbag took place earlier during the ride-down phase, resulting in more efficient restraint of the head. An overview of the driver response data and additional graphs are provided in Appendix II-IV.

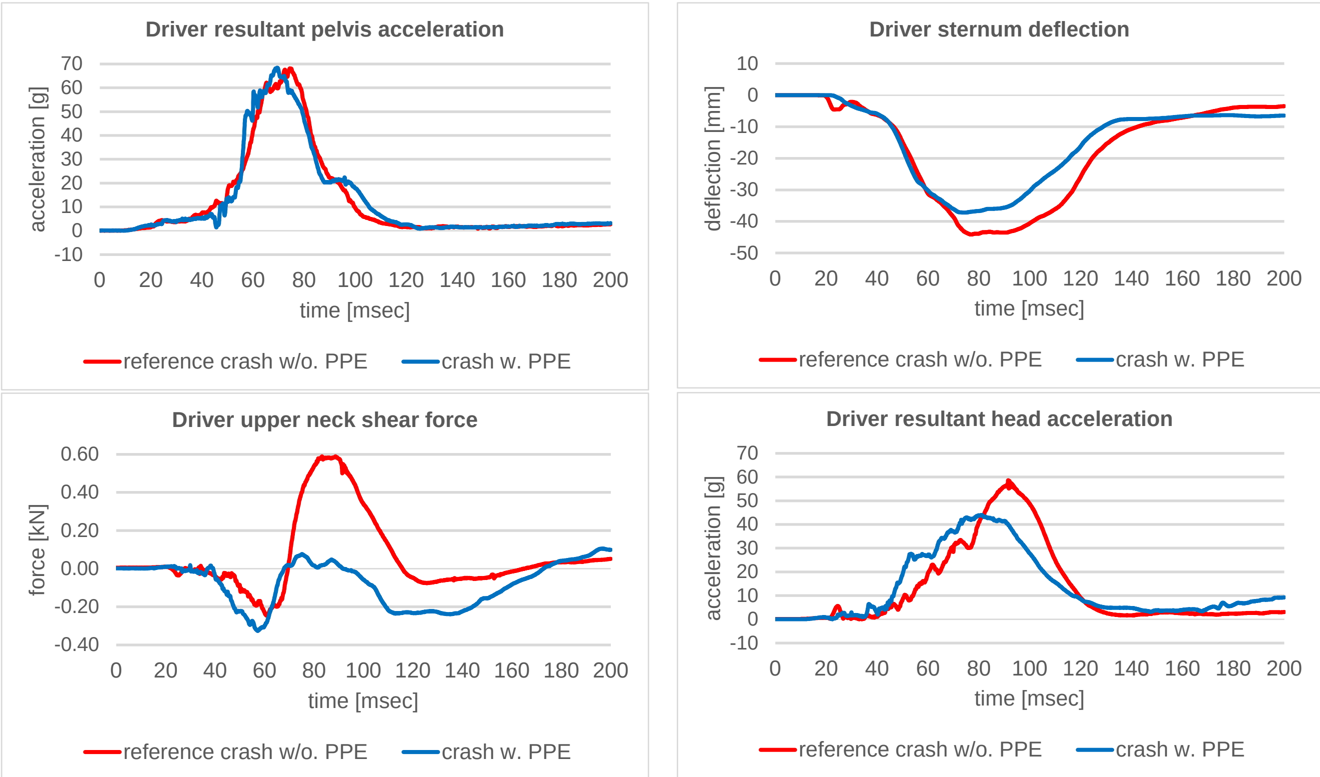

Fig. 6. Comparison of driver loadings in first crash test (reference, without PPE) and second crash test (with PPE), respectively. Pelvis acceleration and sternum deflection (first row), upper neck shear force and head acceleration (second row).

Since the ATD on the passenger seat was not equipped with sensors, the restraint effect on the passenger was assessed only on the basis of the kinematics in both crash tests. Considerably more forward displacement of the ATD's pelvis was visible in the second test with PPE because of more slack in the lap-belt portion and later restraint on the lower body (Fig. 4), similar to the driver. Moreover, as the legs had only modest contact with the passenger-side instrument panel and glove box the pelvis was able to slide forward further on the seat cushion, exhibiting a slightly more pronounced inward rotation of the torso. Nevertheless, the ATD was restrained quite well by the seat belt and the passenger airbag. However, with slightly more forward displacement of the pelvis an increased risk for submarining under the lap-belt could be expected.

The cellulose tissue wrapped around the driver and passenger ATD's neck shields in the second test showed traces of colour, indicating that contact had occurred between the "blade catcher" of the protective vest and the neck shield and underside of the chin. However, neither the videos nor the neck force measurement for the driver suggested that the contact was severe.

As a secondary finding, the handcuffs broke loose from the driver's police belt and the radio unit became detached from the protective vest during the last phase of the ride-down. The injury risk from these flying objects was deemed rather small in this case. Also, no adverse effects were noted by any part of the PPE on the frontal airbag performance.

Behavioural study

Of the 36 officers who participated in the behavioural study, 20 were males (age median: 23 yrs., average: 24.1 yrs.) and 16 were females (age median: 23 yrs., average: 23.8 yrs.). All participants went through the tests as a driver and as a passenger, resulting in a total of 72 datasets for seat adjustment and belt use. In the following, the number of "cases" refers to the combinations of participants and their roles as drivers and passengers, in total 72 cases. The number of "participants" refers to the persons and their characteristics, in total 36.

Female officers were 11 cm shorter than male officers (median height: 172.5 cm vs. 184.0 cm; range for all participants: 164–194 cm). Their arm span was shorter by 11 cm (median arm span: 165.0 cm vs. 176.0 cm; range for all participants: 152–192 cm) and their leg length was shorter by 1 cm (median length: 92.5 cm vs. 93.5 cm; range for all participants: 80–100 cm) in comparison to male officers. When classified into three body height categories, ten participants (all females) fell into the category "shorter than 175 cm", 19 participants (thirteen males, six females) into the category of heights measuring "175–184 cm" and seven participants (all males) into the category "185 cm and taller" (Table A-III, Appendix V).

The pistol was worn on the left side of the body by only 17% of the participants: three female and three male officers. Three female officers chose to carry their pistol on the hip, but all other participants had the holster with the pistol attached to the thigh.

When sitting into the police car, all officers put on their seat belt, whether facing the "patrol scenario" or the "emergency scenario". One driver fastened his seat belt shortly after taking off, but all of the others buckled up immediately after entering their vehicle. None of the participants changed the position of the seat-belt height adjuster. As a result, the position of the shoulder-belt on the shoulder was suboptimal in 46% of cases, altogether. In seven cases (10%; five drivers, two passengers) the shoulder-belt was in an "inward position", i.e. too close to the neck, and in 26 cases (36%; 13 drivers, 13 passengers) it was in an "outward position" over the shoulder. The preferable "centre position" of the shoulder-belt was found in 39 cases (54%; 18 drivers, 21 passengers). (Table A-III, Appendix V). The largest proportion of favourable shoulder-belt path was found among drivers in the medium body height (175-184 cm) category, but was low among short as well as among tall drivers (Fig. 7, left).

However, when evaluating the individual belt position on the participants, it was apparent that the belt path was also influenced by accessories attached to the protective vest, especially in the shoulder region. For instance, carrying the speaker-microphone unit of the radio on the same shoulder where the shoulder-belt runs frequently resulted in a belt position too far outward. A belt path too far inward was found mostly among shorter participants, but also in one passenger measuring 186 cm.

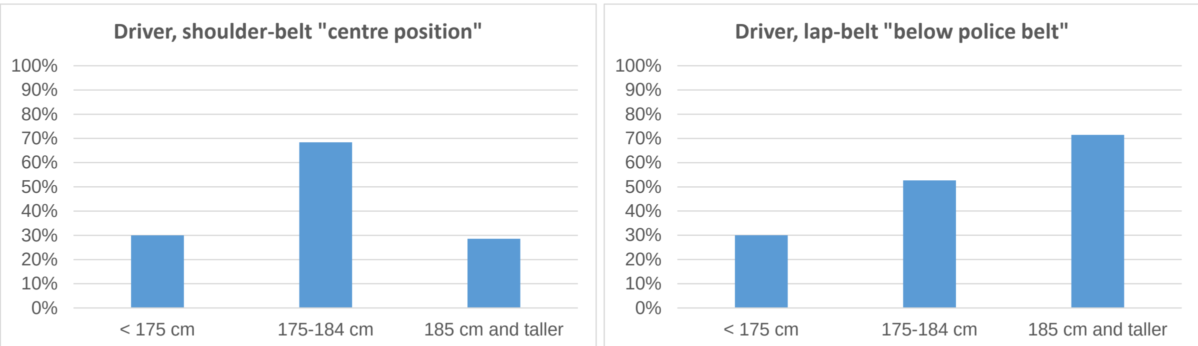

Fig. 7. Proportion of shoulder-belt "centre position" (left) and lap-belt "under police belt" (right) among 36 drivers

In light of the previous crash test results, there was particular interest in the position of the lap-belt. Altogether, in 54% of the 72 cases (22 males, of which: eleven drivers, eleven passengers; 17 females, of which: seven drivers, ten passengers) the lap-belt was arranged "below the police belt" according to the above definition, which was deemed the most favourable position with regard to effective occupant restraint (Fig. 8, left). Again, the lowest proportion of favourable lap-belt path was found among short drivers (< 175 cm), but the highest proportion among tall drivers (185 cm and taller) (Fig. 7, right). Even then, the belt webbing often ran across one item, like the baton, or at times demonstrated considerable belt slack (Fig. 8, centre). In 31% of the cases the lap-belt ran on top of the police belt and across most of the accessories worn on it (“over/across police belt”, Fig. 8, right). In eleven cases (15%) the lap-belt position was “above the police belt”, in the abdominal region. That arrangement was found on eight males (178-191 cm tall), but only on three females (164, 173 and 175 cm tall). When driving in the “patrol scenario”, the lap-belt was worn below the police belt – the preferred position – in 36% of cases, and the shoulder-belt was centred in 53% of cases. The proportions of the lap-belt worn “below the police belt” did not differ much between responding in the “patrol scenario” and the “emergency scenario” (50% vs. 58%). The proportions of the “centre position” of the shoulder-belt differed even less between the “patrol scenario” and the “emergency scenario” (53% vs. 56%).

A minority of participants, only 7% (five cases, of which one driver, four passengers), were documented as actively pulling the seat belt tight after buckling up, all being in the “patrol scenario”.

The default seat track position was maintained in 48 cases. In the remaining 24 cases the seat was moved forward (17 drivers, all except one shorter than 185 cm; seven passengers, 173-194 cm tall). The seat height was changed from its lowest, i.e. the default position, only once. The steering column position was adjusted slightly in four cases.

None of the differences identified for the proportions of belt fit was of statistical significance.

Fig. 8. Acceptable lap-belt path, outward shoulder-belt position (left), lap-belt under holster with extreme belt slack (centre), lap-belt over police belt and several accessories, acceptable shoulder-belt path (right).

IV. Discussion

Manufacturers of automobiles have invested considerable effort over the past decades to improve occupant protection in crashes. Seat belts were enhanced with D-ring height adjustment to improve belt fit for a variety of occupant heights and pretensioners were introduced to minimise belt slack when belts do not fit tightly on the body, i.e. when thick clothing is worn. However, the problems posed to occupant crash protection when PPE is being worn by police or other first responders have received little attention so far, even though the risk of being involved in a traffic accident is relatively high for this group due to exposure, in general, and potentially hazardous situations when responding to emergencies.

The initial motivation of the present study was to evaluate the potential injury risk in car crashes for police officers when wearing a specially designed protective vest to prevent chest and neck wounds from knife assaults. The frontal crash test conducted with ATDs wearing special police gear did not indicate an imminent risk from the protective vest in the neck area, although contact did occur. The chest deflection measured on the driver ATD even suggested that a properly worn protective vest may distribute the force acting from the shoulder-belt on the thorax. However, the Hybrid III ATD chest design has been criticised because it was developed using hub-impacts and chest deflection lacks sensitivity to different modes of restraint loading, e.g. whether by a seat belt or an airbag [8]. This limitation might possibly be overcome in the future if more tests with protective vests and a more advanced ATD, like the THOR, were conducted to confirm a potential injury reducing effect on the thoracic area. On the other hand, the comparative tests revealed that the police belt with holster and pistol plus the assortment of accessories represents a major challenge for a properly routed lap-belt. Although care was taken in the crash test to place the lap-belt portion below the police belt and provide the best possible interaction with the ATD's pelvis and despite buckle pretensioning, the test demonstrated more forward excursion and increased lower extremity loading in comparison to the reference test without police gear. However, positioning the lap-belt above or across the police belt and the items attached to it poses a considerable risk that the lap-belt might slip over the iliac crest in a severe crash, resulting in a submarining motion and pulling into the abdominal area. Rigid items like the baton or pepper spray can that are often worn on the front of the police belt may pose an additional injury risk for the abdomen or soft tissue in a severe frontal crash. Standard ATDs used for crash tests are not suited to assess this type of injury.

Vehicles with knee airbags for frontal protection may offer additional support for restraint of the lower body where optimal function of the lap-belt is compromised. However, these systems are designed and tested for properly belted occupants and vehicle manufacturers provide them, if at all, mostly for the driver side.

Positioning the belt webbing below the police belt and accessories is more demanding and time consuming, both when buckling up and unbuckling, and may hinder entering and leaving the vehicle swiftly in emergencies. Therefore, concerns are warranted whether this much care is exercised by police personnel in real life when fastening their seat belts. The behavioural study with young police recruits provided further insight into the belt use patterns in a realistic environment and revealed specific problems of securing oneself as a fully equipped officer.

The behavioural study part also has some limitations. The number of participants was too low and the variety of variables influencing belt fit too numerous for detailed statistical evaluation. While the true background of the tests was not disclosed to the participants, there is a possibility that some participants acted unnaturally because this was obviously a laboratory setting. Also, some conversation between participants who had already completed the course and those just about to participate may have taken place. On the other hand, switching the roles between drivers and passengers and between the two scenarios minimised the possibility of adjusting to the task in advance. The chosen group of participants was quite homogeneous as it consisted of recruits of similar age, in good physical shape, with a comparable level of training and practical experience in police duty. Therefore, no direct conclusions should be drawn with regard to the behaviour of police officers with several years of service and a larger variety of physical conditions, including weight and body-mass index, and training. The finding from Canada that police officers involved in traffic accidents had served nine years, on average [3], suggests that officers might become more negligent with regard to to traffic safety precautions, in general, with longer service time. Further studies would be required to substantiate this assumption.

With regard to the results from the behavioural study, it must be stressed that all participants put on their seat belt, almost without exception, before starting their drive. The large percentage of unbelted officers who were ejected from their vehicle in fatal accidents in the U.S.A. [2] underlines the importance of belt use and first priority among safety precautions. Yet, almost none of the participants in this study wore the seat belt in the preferred manner from the perspective of optimal occupant protection. While some negligence or lack of knowledge may be suspected in a few cases, the urgency and stress placed on the participants, especially in the "emergency scenario", likely played a role that was reflected in the higher rate of unfavourable belt positions. Interestingly, a few female officers demonstrated rather favourable routing of the lap-belt. They were of smaller stature, on average, and this fact may have facilitated a steeper lap-belt angle on their hips and easier positioning below the police belt. In addition, it was noted that women's uniform trousers are tailored to have a higher waist, likely resulting in the police belt also being worn higher on the body.

Of even greater importance is the fact that the accessories and pockets that individuals had attached to the police belt and the protective vest often did not allow an optimal seat-belt path. The position of these items on the PPE is determined by personal preferences. Some of them may be not negotiable, like the side on which the pistol and the speaker-microphone unit of the radio are worn. Other items, like the flashlight or handcuffs, may be positioned more freely without compromising quick access when needed. Ideally, most of the items would be positioned so that they interfere as little as possible with the belt webbing and do not produce additional injury risk in case of a frontal or side collision. This may prove difficult for larger, rigid objects like a baton, flashlight or pepper spray can. Other items, like the notepad or the radio unit, are stowed in pockets attached to the protective vest by Velcro strips. That offers some flexibility to arrange them in such a way that a good shoulder-belt path is provided. While that may be an option for officers who are regularly on duty either as a driver or a passenger, one has to bear in mind that an optimal arrangement of accessories – with respect to belt routing – may prove disadvantageous when changing the seating position in the vehicle due to inverted seat-belt geometry.

A holster with a pistol will always be positioned on the officer's hip or thigh, either facing the seat-belt buckle and centre console or facing the outside. In the latter case, they are in the immediate area of door intrusion in the event of a severe side impact, as shown in the Swedish crash tests [5], and may increase the risk for fractures, particularly in the hip joint region. Also, examples from the behavioural study demonstrated that this region could be exposed directly to hard contact with the pistol or holster when worn at hip level. Moreover, the lap-belt often ran across the weapon or was at risk of getting caught under the holster, which prevented a tight fit on the pelvis. Even when the lap-belt was routed below the police belt – the preferable position from the perspective of occupant restraint – some participants demonstrated enormous belt slack because large items like the pistol and holster or the baton interfered with the seat belt. Pistols worn at lower level in a thigh holster demonstrated much less interference with the seat-belt webbing and, in addition, were situated out of the immediate contact zone with the hip joint.

V. Conclusions

The present study highlights the problems involved for vehicle occupants wearing PPE when seeking to put on their regular three-point seat belt properly. This likely pertains not only to police personnel but also to other first responders or members of the military when wearing special uniforms and gear.

While military vehicles or fire-fighting vehicles, for instance, may offer possibilities to customise seat-belt systems in order to account for some of these challenges, this is not possible for most police or ambulance vehicles because they are usually based on regular production models. Thus, efforts to improve seat-belt fit on the occupant must focus on the PPE and user behaviour. Further research is necessary to evaluate possibilities to avoid interference of the vehicle seat belt with the police belt and other accessories worn on the body without compromising their function and protective effect while outside the vehicle. New concepts or configurations of PPE arising from such work should be confirmed in dynamic tests in a vehicle environment first, before issuing recommendations or instructions for use.

Notwithstanding these limitations, it is recommended that standard training of first responders ought to stress the importance of putting on the seat belt, to raise awareness of proper belt fit on the body and warn of the potential hazards that could arise from the use of PPE.

VI. Acknowledgements

The authors would like to thank officers Carolin Schöberl, Bastian Stoiber and Till Thüring for their contribution to the discussion and their assistance in conducting the behavioural study.

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VIII. Appendix

Appendix I

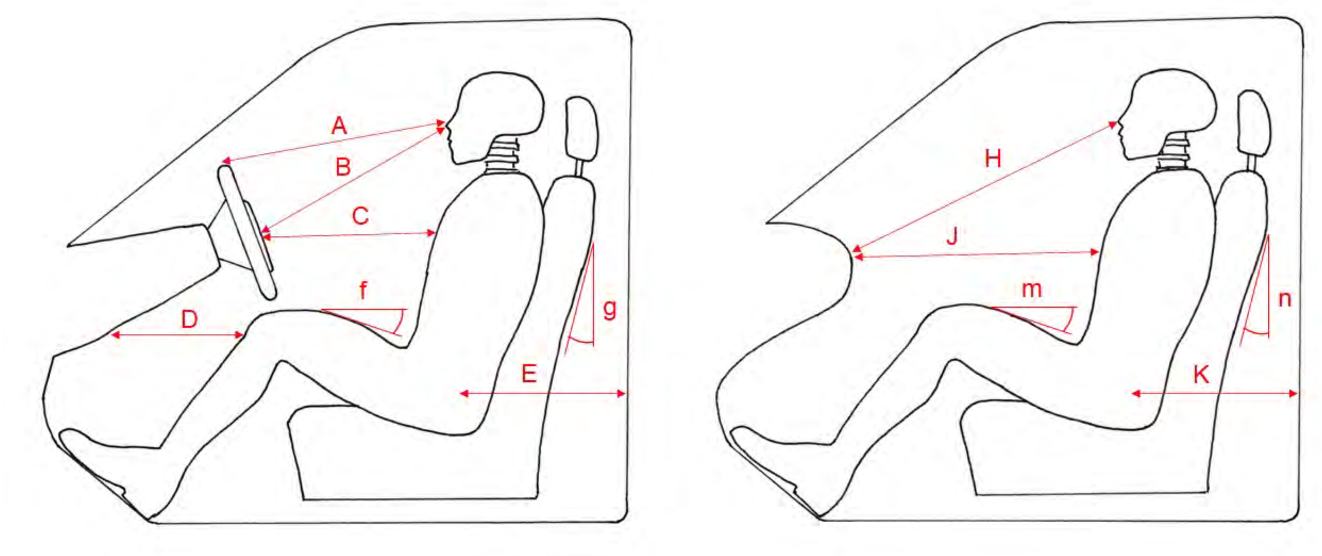

Fig. A-1. Key dimensions for positioning Hybrid III midsize male ATDs on driver and front-passenger seat

TABLE A-I
DRIVER AND PASSENGER KEY DIMENSIONS IN VEHICLE ENVIRONMENT

	Reference crash test without PPE		Crash test with PPE	
	driver	passenger	driver	passenger
A: Nose to top of steering wheel rim [mm]	495		382	
B: Nose to driver airbag centre [mm]	441		350	
C: Chest (sternum)/protect. vest to driver airbag centre (horizontal) [mm]	336		235	
D: Left knee to lower instrument panel (horizontal) [mm]	155		150	
E: H-point to front edge of B-pillar (horizontal) [mm]	169		202	
f: Femur angle [°]	19		13	
g: Seat back cover angle [°]	115		115	
Lateral distance left knee to right knee (centre) [mm]	327		325	
H: Nose to front edge of instrument panel [mm]		661		602
J: Chest (sternum)/protect. vest to front edge of instrument panel [mm]		535		492
K: H-point to front edge of B-pillar (horizontal) [mm]		173		206
m: Femur angle [°]		12		9
n: Seat back cover angle [°]		115		115
Lateral distance left knee to right knee (centre) [mm]		328		318

Note: Addition of PPE puts ATD torso forward by 20-50 mm and reduces distance to interior by 40-100 mm

APPENDIX II

Fig. A-2. Comparison of driver ATD responses in first crash test (reference, without PPE) and second crash test (with PPE), respectively. Upper neck (first row), left femur and left lower tibia (second row) and knee (third row).

APPENDIX III

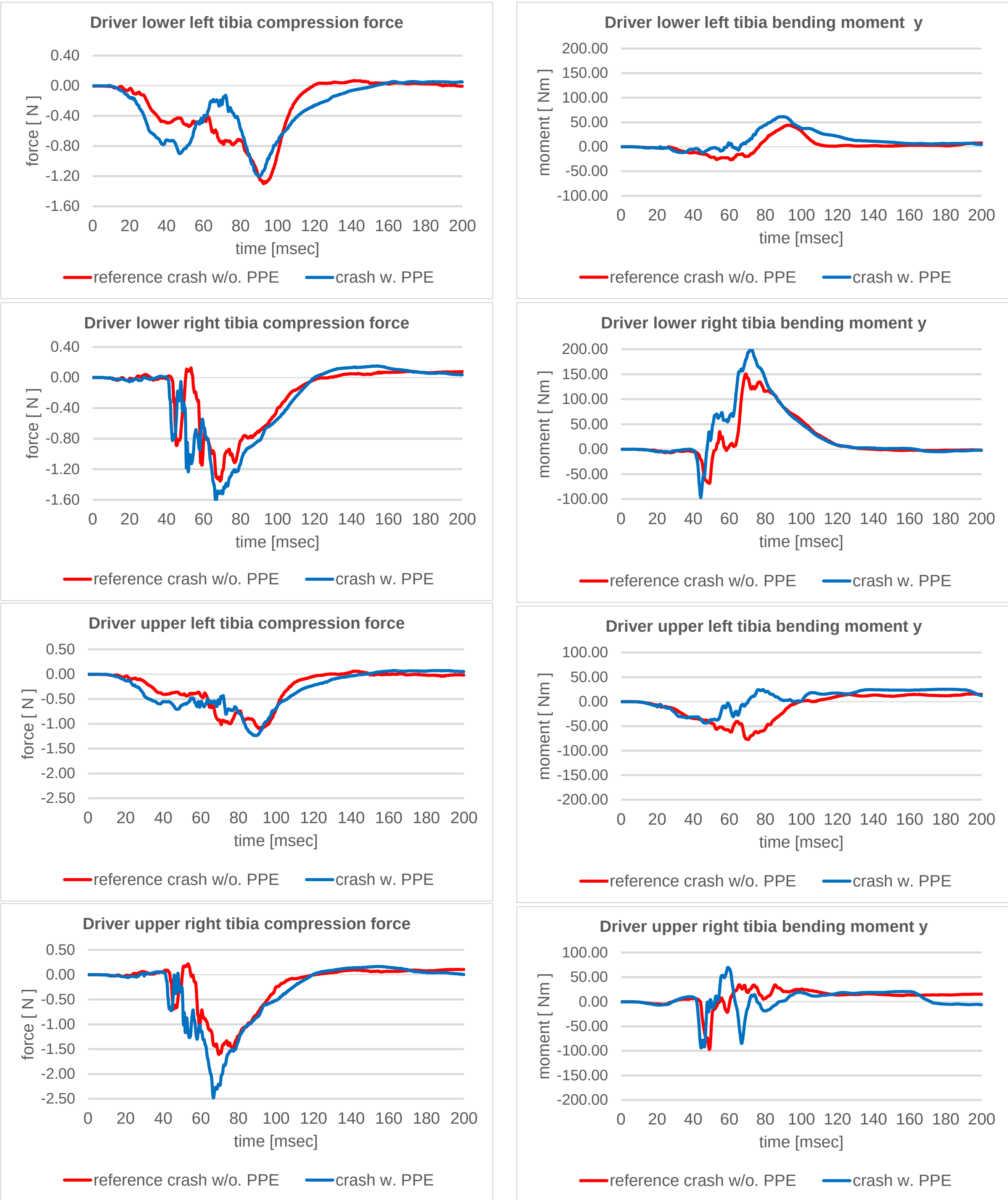

Fig. A-3. Comparison of driver ATD tibia force and moment responses in first crash test (reference, without PPE) and second crash test (with PPE), respectively. Lower left tibia (first row), lower right tibia (second row), upper left tibia (third row), upper right tibia (fourth row).

APPENDIX IV

TABLE A-II
DRIVER RESPONSE PEAK VALUES IN TESTS WITH AND WITHOUT PPE VS. EURONCAP LIMITS

Driver ATD response (maximum absolute value)	Reference test without PPE	Test with PPE	EuroNCAP higher performance limit	EuroNCAP lower performance limit
Head HIC 15 [-]	317	178	500	700
Resultant head acceleration (3 msec) [g]	55	43	72	80
Upper neck shear force [kN]	0.6	0.1	1.9	3.1
Upper neck tension force [kN]	1.3	1.7	2.7	3.3
Upper neck extension bending [Nm]	15	13	42	57
Chest compression (sternum deflection) [mm]	44	37	35	60
Resultant pelvis acceleration (3 msec) [g]	65	65	-	-
Left femur compression force (peak value) [kN]	1.38	2.40	3.80	9.07
Right femur compression force (peak value) [kN]	3.49	5.66	3.80	9.07
Left knee slider compress. displacement [kN]	0.1	1.5	6	15
Right knee slider compress. displacement [kN]	3.8	4.7	6	15
Upper left tibia compression force [kN]	1.1	1.2	2.0	8.0
Upper right tibia compression force [kN]	1.6	2.5	2.0	8.0
Upper left tibia bending moment M_y [kN]	77.3	43.8	-	-
Upper right tibia bending moment M_y [kN]	97.1	94.0	-	-
Lower left tibia compression force [kN]	1.3	1.2	2.0	8.0
Lower right tibia compression force [kN]	1.4	1.6	2.0	8.0
Lower left tibia bending moment M_y [kN]	43.7	61.2	-	-
Lower right tibia bending moment M_y [kN]	150.8	202.8	-	-
Upper left Tibia Index [-]	0.4	0.3	0.4	1.3
Upper right Tibia Index [-]	0.5	0.6	0.4	1.3
Lower left Tibia Index [-]	0.2	0.5	0.4	1.3
Lower right Tibia Index [-]	0.9	1.1	0.4	1.3

APPENDIX V

TABLE A-III
OVERVIEW OF SEAT BELT AND PPE POSITIONING AND BODY HEIGHT OF PARTICIPANTS

		Driver, male (n=20)	Driver, female (n=16)	Passenger, male (n=20)	Passenger, female (n=16)	Patrol scenario (n=36)	Emergency scenario (n=36)
Shoulder-belt on shoulder	inward	2 (10%)	3 (19%)	1 (5%)	1 (6%)	5 (14%)	2 (6%)
	centred	9 (45%)	9 (56%)	13 (65%)	8 (50%)	19 (53%)	20 (56%)
	outward	9 (45%)	4 (25%)	6 (30%)	7 (44%)	12 (33%)	14 (39%)
Lap-belt relative to police belt	below	11 (55%)	7 (44%)	11 (55%)	10 (63%)	18 (50%)	21 (58%)
	over/across	5 (25%)	7 (44%)	5 (25%)	5 (31%)	13 (36%)	9 (25%)
	above	4 (20%)	2 (13%)	4 (20%)	1 (6%)	5 (14%)	6 (17%)
Pistol holster	on hip	0 (0%)	3 (19%)	0 (0%)	3 (19%)	33 (92%)	33 (92%)
	on thigh	20 (100%)	13 (81%)	20 (100%)	13 (81%)	3 (8%)	3 (8%)
Position of pistol	left side	3 (15%)	3 (19%)	3 (15%)	3 (19%)	6 (17%)	6 (17%)
	right side	17 (85%)	13 (81%)	17 (85%)	13 (81%)	30 (83%)	30 (83%)
Position of speaker-mic unit of radio	left shoulder	13 (65%)	11 (69%)	14 (70%)	11 (69%)	24 (67%)	25 (69%)
	right shoulder	7 (35%)	5 (31%)	6 (30%)	5 (31%)	12 (33%)	11 (31%)
Body height	< 175 cm	0 (0%)	10 (63%)	0 (0%)	10 (63%)	10 (28%)	10 (28%)
	175-184 cm	13 (65%)	6 (38%)	13 (65%)	6 (38%)	19 (53%)	19 (53%)
	> 184 cm	7 (35%)	0 (0%)	7 (35%)	0 (0%)	7 (19%)	7 (19%)
Seat track position	neutral	13 (65%)	6 (38%)	15 (75%)	14 (88%)	24 (67%)	24 (67%)
	forward	7 (35%)	10 (63%)	5 (25%)	2 (13%)	12 (33%)	12 (33%)

Note: Counts and percentage values for equipment worn by males and females remained the same for their driver and passenger role and for the patrol and emergency scenario (except for one male participant who switched the position of the speaker-microphone unit of his radio between the two test rounds).

ERRATUM

Effects of personal protective equipment worn by police officers on restraint system performance in frontal crash

Axel Malczyk, Antonio Pedron, Christoph Zinner, Gerd Mueller

After publication it was discovered that percentage values were incorrectly reported in two places of the paper and that in one sentence the wording should to be changed to avoid misunderstanding:

In RESULTS, *Behavioural study*, page 10, first paragraph, the fifth sentence should be:
“When driving in the “patrol scenario”, the lap-belt was worn below the police belt – the preferred position – in **50%** of cases, and the shoulder-belt was centred in 53% of cases. “

In APPENDIX V, TABLE A-III, OVERVIEW OF SEAT BELT AND PPE POSITIONING AND BODY HEIGHT OF PARTICIPANTS, in columns “Patrol scenario” and “Emergency scenario”, the reported numbers and percentages between *Pistol holster* “on hip“ and “on thigh“ were switched. The correct numbers and percentages are given below.

		…	…	…	…	Patrol scenario (n=36)	Emergency scenario (n=36)
Pistol holster	on hip	…	…	…	…	**3 (8%)**	**3 (8%)**
	on thigh	…	…	…	…	**33 (92%)**	**33 (92%)**

In DISCUSSION, page 11, fifth paragraph, the fourth sentence should be:
“While some negligence or lack of knowledge may be suspected in a few cases, the urgency and stress placed on the participants, especially in the “emergency scenario”, likely played a role that was reflected in the **high** rate of unfavourable belt positions. “