TECHNICAL PARAMETERS AND MECHANISMS FOR KNEE JOINT INJURIES TO BELTED CAR DRIVERS IN ROAD TRAFFIC ACCIDENTS

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ABSTRACT
This paper describes the risk of the knee joint injury for belted car drivers in traffic accidents. The situation for knee injuries has been influenced by the changing of interior design of vehicles, including the dashboard and restraint systems like seatbelts, pretensioners and airbags over recent decades. An analysis of real world accidents was carried out by ARU-MUH (Accident Research Unit at Medical University Hannover) utilizing accident data gathered under the in-depth-investigation methodology practiced by the GIDAS (German-In-Depth-Accident-Study) multi-disciplinary research team. GIDAS document accidents on-the-spot, using a sampling process to ensure that results are representative for the German traffic accident situation.

Accident documentations from 1985 to 2003 are used for this study. Two different groups of accident data were compared: the years 1985 to 1993 (n=536 people with knee injury rated AIS1, n= 81 people with knee injury rated AIS2+, n= 7260 injured people without knee injury), and 1995 to 2003 (n=451 people with knee injury rated AIS1, n=48 people with knee injury rated AIS2+, n= 9372 injured people without knee injury). The study describes the frequencies of knee injuries on soft tissue knee lesions rated AIS1 and injuries to ligaments and fractures rated AIS2+. In addition, knee injury risks are evaluated by comparing results with the group of drivers without knee injury. The study shows that there is, nowadays, a low risk of severe knee injuries rated AIS 2+ for seat-belted car drivers (0.4% of all injured drivers, documented years 1995 to 2003). It can be pointed out comparing the results with previous studies, that knee injury risk for belted drivers in German car accidents is much lower than that expected from investigations in other countries. The classical dashboard injury that could be seen in the past, very often involving fractures of the acetabulum plus patella plus rupture of rear cruciate ligament can no longer be seen in accidents today. A fracture of the patella could be established in the current accident sample for only 0.1% of all injured belted car drivers. Patella fractures are an indicator of axial load, observed in 43% of the AIS2+ knee injury cases (n=44). The number of patella fractures is directly proportional to delta-v and intrusion. A femur fracture was found in 25 %, and a fracture of the acetabulum was found in 5 % of the knee injured cases. Ruptures of the cruciate ligaments are observed relatively seldom (7.5% of AIS2+ knee injured occupants). These results express a good level of passive safety in cars today.

Keywords
Knee injury, Knee fracture, Occupant safety, bony and ligament injuries of knee

DUE TO TRAFFIC ACCIDENTS costs of more than 160 billion Euro (ETSC 2001) arise annually, not counting the pain and long term pattern. The causes for the high economic cost are monetary and non-monetary expenses of the public sector for treatment and consequences of the injuries that result from an injury pattern of a casualty. Even though a decrease of the degree of severity of an accident and today frequently less severely injured persons can be registered demonstration the progress in accident safety protection against injuries, to allow many more road users than formerly to survive. Still many injuries occur that are considered as light concerning their severity, but are important regarding the long-term consequences for the injured persons. Thus a calcaneus fracture that occurs sporadically, frequently results in a reduction of working inability of 25 %. The socio-economic costs of many injuries resulting in handicaps, such as whiplash injury and injured ligaments at the extremities are currently insufficiently assessed regarding their degrees of severity, which is generally measured regarding the risk of death (AIS Abbreviated Injury Scale 1998) as less severe. This applies especially to injuries of the lower extremities involving foot, ankle joint and especially the knee. In the
early 70s, knee injuries ranked high among the frequency of injuries of occupants of cars. The so-called “dashboard injuries” constituted - based on the special injury pattern of injuries to knee and thigh as well as pelvis trauma - a main focus on the degree of severity of the patients (Mosheiff et al 1998). Already at that time there were more calls for improvements of the safety of cars (Fildes et al 1997). Most of the authors reported on the risk of knee injuries for unbelted situations. Lower limb injuries occurred to front seat occupants in more than one in three head-on crashes involving injuries. The most frequent lower limb fractures by contact source combinations were ankle/foot with the floor & toe pan, lower leg with the floor & toepan, thigh with the instrument panel, lower leg with the instrument panel, knee with the instrument panel and knee with the steering column. Thomas showed in a study presented at the 14th ESV Conference that intrusion constitutes a risk parameter - independently of the severity of the collision, delta-v (Thomas 1995). He found knee-injuries for 12% out of 4094 drivers using a seatbelt in head-on collisions and found that 30% of the fractures of the leg occurred without intrusion. Dischinger (2004) found out in a US study for accidents from the years 1991 to 1994 that men suffered more frequently from fractures of the pelvis and women from fractures of the lower extremities. Patella fractures occurred in 2% of the cases with drivers using a seatbelt, more frequently with airbags than without. Persons suffering from knee injuries cause the second highest costs for medical treatment today. For the emergence of knee injuries the impact situation of the vehicle plays an important role. Kallina (1995) pointed out that especially in offset frontal collisions there is a high risk. This mechanism was already known as „Impact Shock Syndrome“. Hollowell (1995) also stated that intrusion related injuries occur more frequently in cases of an offset crash than in cases of a full frontal impact. Intrusion results in a reduction of the angle between the level of the foot and the longitudinal axis of the tibia, which in turn results in a reduced distance of the patella to the dashboard when the body moves forward (Daniel 1995). However, car occupants are rarely among the especially risk exposed traffic participants with knee injuries. These injuries occur especially frequently among the so-called "vulnerable road users". According to own investigations about 36% of the motorcyclists, 25% of the bicyclists and 22% the pedestrians in traffic accidents suffer knee injuries of the degree of severity AIS 1+, whereas only 10% of the car occupants are affected (Otte 2005). The introduction of the safety belt, continuously optimized safety features and equipment in cars, with padding and ‘defusing’ of the dash board resulted in this significant reduction of the risk of knee injuries in a car accident.

TARGET AND METHODOLOGY

It is the target of this study to examine the injury pattern of belted car occupants especially concerning knee injuries and to correlate these with accompanying injuries at tibia, femur and pelvis with regard to incidence and characteristics as well as the injury mechanics.

In order to correctly investigate the injury patterns of car occupants in detail that currently occur in traffic accidents, investigations are conducted on scene at the site of the accident. A team of physicians and engineers drives to the scene of the accident and documents the vehicle deformation, accident traces and injuries of the occupants (Otte et al 2003). The data collection is carried out by order of the Federal Highway Research Institute (BASt). Accidents involving personal injury are investigated according to a statistical sampling process. In both areas, the respective police, rescue services, and fire department headquarters report all accidents continuously to the research team. The team then selects accidents according to a strict selection process and investigates these cases following detailed procedures contained in a handbook and coding manual. In order to avoid any bias in the database, the data collected in the study is compared to the official accident statistics for the respective areas and weighting factors are calculated annually. This process explains why the data captured by the research teams can be seen as representative for their areas (Hautzinger 2004). The exact diagnoses of the injured occupants are collected from the treating hospitals and can be allocated to the sources of injuries in the vehicles at a later stage. On the basis of scaled drawings and a technical impact analysis a comprehensive reconstruction of the vehicle motion sequence and the accident severity that occurred is determined. Accident characteristics, such as Delta-V, EES or deformation depth are correlated to the classified injury severities.

The injuries were documented using independent documentation and the inspection of medical diagnosis reports and x-ray images. The documentation contains graphical material and drawings of the accident traces at the site of the accident, detailed measurements of the damages to the vehicle are
taken and an accident reconstruction of the motion sequence using computer aided simulation (PCcrash) is conducted. With this data the origin, the type and the extent of the injuries can be determined. The classification of the injury severity was done according to AIS (American Association for Automotive Medicine 1998). The documentation was conducted using the same methodology for the whole period of data collection, which allowed for a statistical comparison of the accident structure between cases from the past and nowadays. These cases were checked by an experienced surgeon based on the AIS-classification and the medical evaluations of the injury patterns of the knee were defined. Based on the analysis of technical data and photographs the analysis of the accident mechanism and the accident load from the technical point of view was also conducted. Subsequently the analyzed characteristics were coordinated and evaluated for statistic relevance using statistic tests.

SPECIAL SAMPLE OF KNEE INJURED BELTED OCCUPANTS

n=16563 accidents with personal injury of the years 1985 to 2003 of the ARU-MUH were evaluated. 14882 cars with belted drivers were involved, out of which 5976 drivers were injured. These were sorted according to knee injuries.

For purposes of analysis three different samples were distinguished, those without knee injuries (n=5091), those with slight knee injuries of the degree of severity AIS 1 (n=799) and those with severe knee injuries AIS 2+ (n=82).

After grouping the cases that occurred in the years 1985-1993 and 1995-2003 all cases of knee injuries with a degree of severity AIS 2+ were separated (85-93 n=56; 95-03 n=26) and were subjected to a specific interdisciplinary technical and medical analysis in detail. For this purpose injury mechanisms were evaluated (n=82) that were effective during the impact and afterwards affected the knee unit. Furthermore the position of the knees in the seated position that had been derived from the accident reconstruction was taken into account and the occurring kinematics were evaluated according to the resulting damages in the interior as well as the impact vector and the resulting relative motion of the occupants of the car.

Injuries of the knees range from the distal femur epiphysis with condyles to the head of the tibia with epiphysis, as well as all connecting structures, ligaments including bone insertion, menisci and the patella as well as the soft tissue surrounding these structures (figure 1).

![figure 1 anatomical regions of knee (ligaments and bony structure)](image)

The AIS classification considers contusions and smaller soft tissue lesions as AIS 1, soft tissue injuries of a greater extent (distortions) with injuries of bursa, ligaments or menisci, patella fractures, non-compound and only slightly shifted fractures of the tibia, knee dislocations or an open joint are allocated AIS degree 2. Fractures of the distal femur, compound or comminuted proximal tibia fractures, full rear cruciate ligament ruptures and open ligament ruptures are classified as the highest
degree of injury severity AIS 3. Additionally, the classification of the different tibia plateau fractures according to Schatzker was used (Stevens 2001) which is known from scientific clinical diagnostics and classifies the degree of severity from 1 to 6.

INCIDENCE AND TYPOLOGY OF KNEE INJURIES
Severe knee injuries AIS 2+ among car occupants wearing seat belts today are only found in 0.4 % of all accidents with cars resulting in bodily damage (figure 2), which is significantly less frequently than in the 80s and beginning 90s (1986 to 1993). At that time, with 1.2% the risk of severe knee injuries was three times as high as in the late 90s and beginning of this millennium. It can also be seen that formerly about one twelfth of the knee impacts resulted in severe knee impact traumata whereas light injuries AIS 1 had occurred in 14% of the cases. In contrast only 1/25 of all knee impacts result in severe injuries to the knee (9.8% AIS 1/0.4% AIS2+) today.

![figure 2](image)

**figure 2**  ratio of knee injuries in traffic accidents on injured belted drivers (100% each group)

If the different types of collisions of a car are taken into account (figure 3), it is not surprising that 60% of the AIS 2+ knee injuries occur in the course of head-on collisions. But the fact that knee injuries occur more frequently after impacts from the left side is remarkable, as this shows that even in positions pointing away from the impact knee injuries occur.

![figure 3](image)

**figure 3**  distribution of impact areas of cars for different groups of belted injured car drivers with knee injuries AIS 1, AIS 2+ and without knee injury for accidents of years 1985-93 compare to years 1995-2003 (100% each group of injury severity knee)

In nowadays accidents 56.6 % of knee injuries AIS 1 and 60.2 % of AIS 2+ occurred at frontal impacts (figure 3), 8.7 % of the knee injuries AIS 1 and 8.4 % with AIS 2+ occurred at impacts from
the left or nearside, whereas only 5.4 % of the AIS 1 and only 3 % of the AIS 2+ injuries occurred in the case of an impact from the right or far side.

The greatest risk of suffering from knee injuries is without doubt in case of frontal collisions at 16.8% AIS 1 and 1.3 % AIS 2+, but knee impact traumata occur also in cases of side impacts. 0.5 % of the impacts from the left and 0.3 % if the impacts from their right side caused knee injuries AIS 2+ to drivers (figure 4).

Even for rear end collisions knee impact situations have been observed, but exclusively AIS 1 (1.5%). At Multiple collisions containing frontal impacts as well as impacts from the side, 0.7 % result in knee injuries AIS 2+. As approximately one third of all collisions are multiple collisions, a large proportion of the persons with AIS 2+ knee injuries were injured in the course of multiple collisions.

In lateral collisions the oblique impact angle seems to be an important parameter for knee injury occurrence as shown in the following figure. No cases resulting in knee injuries AIS 2+ were found at nearly perpendicular impact conditions (figure 5).

Newer vehicles are obviously safer and prevent more knee injuries, as shown in this study. For nearly all kinds of collisions the amount of knee injuries AIS1 und AIS 2+ is less than half in newer vehicles.

It can be seen that 80% of the cars involved in the accident sample 1985 to 1993 were older than 1988 and 80% of the accident sample 1995 to 2003 were younger than 1988 (figure 6).
TYPE OF KNEE INJURIES AND ACCIDENT SEVERITY

Knee injuries AIS 2+ are only found at higher accident severity. One relevant parameter for measuring the accident severity is the speed change value delta-v. Differentiated according to frontal and side impact it can be shown that with increasing delta-v the incidence of a knee impact resulting in a knee injury of the degree of severity AIS 1 as well as AIS 2+ increases.

Especially in nowadays accident situations a low risk of knee injuries can be found (figure 7). Up to delta-v-values of 50 km/h the ratio of knee injuries AIS 2+ is less than 1 %. Also soft injury lesions AIS 1 are significantly less over the whole range of delta-v-values comparing the past and the current accident situation.
Knee injuries and especially their severity AIS1 and AIS 2+ correlate with the accident severity delta-v. 80% of the delta-v values of belted drivers with knee injuries AIS 2+ can be found above delta-v = 30 km/h, whereas for drivers without knee injuries 80% of all collisions occurred at delta-v values lower than 40 km/h (figure 9).

Knee injuries AIS 2+ occur among the most severely injured occupants of cars. Whereas 5.1% of the car drivers suffered slight knee injuries AIS 1 and 3.2% of those not injured at the knee had an overall MAIS 3+ injury severity, 54.7% of the drivers who were injured AIS 2+ at the knee suffered from injuries of a degree of severity MAIS 3 or higher (figure 10).
Concerning the injury pattern, persons with severe knee injuries AIS 2+ also have injuries of the head (72.6% of the persons), thorax (46%) and the arms (52.3%) (figure 11). It is significant that for persons suffering from severe knee injuries in contrast to persons with slight knee injuries or no knee injuries, the proportion of so-called whiplash injuries of the neck occurred significantly less frequently (12.8% compared to 33.4% and 46.2%). However all other body regions were more severely injured with increasing severity of the knee injuries. The pelvis is injured four times as often at persons with AIS 2+ knee injuries than at drivers without knee injuries. Arm and head and abdomen are injured double as often.

Concerning ligament injuries, the medial collateral ligament (11.2%) was affected more frequently than the lateral collateral ligament (2.2%) and the anterior crucial ligament (10.1%) was affected more frequently than the posterior crucial ligament. Outer und inner menisci were injured only in 0.8 % of the cases.
Severe knee injuries are connected to an intrusion into the passenger compartment. In frontal impacts of cars 43% of the cases with belted drivers with AIS 2+ knee injuries showed an intrusion of the compartment and 32.7% of the cases in lateral collisions showed an intrusion of the compartment (figure 13). In contrast only 14% of the cases with light AIS 1 soft tissue lesions of the knee and only 7.4% of the cases who were not injured at the leg (16.3% or 12% for a lateral deformation) showed an intrusion of the compartment.

Intrusion plays an important role in the occurrence of severe injuries to the knee. As figure 14 shows, 70% of the cars of the drivers with knee injuries AIS 2+ had an intrusion at delta-v above 40 km/h. comparing to those without intrusion where nearly 2/3 delta-v values can be seen up to 40 km/h. 80% of all belted car drivers without knee injuries had accidents with delta-v values less than 40 km/h.
Only 54.7% of the car occupants with severe knee injuries AIS 2+ did not suffer accompanying injuries of the lower leg, foot, thigh and pelvis. 22.8% of the car occupants suffered a fracture of the thigh, 13% of the pelvis, 18.8% of the lower leg, 9.6% of the foot and ankle and 0.9% suffered a fracture of the hip.

Patella fractures are present in 27.1% of the cases of femur fractures and in 18.2% of fractures of the lower leg (table 1). The area of the foot is still relatively frequently injured with 11.7%. Ligament injuries frequently also come along with injuries of the lower leg or foot. Collateral ligament lesions (medial as well as lateral) are linked with pelvis injuries (30%/50%). This characterizes the extreme torsion of the foot and lower leg resulting in tensile loads in the ligament structures of the knee. In case of meniscus lesions, solely fractures of the lower leg had occurred.

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Thus severe knee injuries are correlated to intrusions of the passenger compartment in 32.7% of the cases, even with deformation in the footwell or the dashboard areas.

Nearly all ligament ruptures documented here occurred solely at high delta-v values of above 40 km/h. Patella fractures, fractures of the femur condylus and tendon ruptures can be seen at delta-v > 20 km/h (figure 15).
Types of knee injuries and value of delta-v in frontal collision (n=42), circle without intrusion, dot with intrusion

The estimated mean delta-v-value shows this correlation for the occurrence of different types of knee injuries (figure 16). While belted car drivers without any knee injury had mean delta-v-values of 29.4 km/h, those with knee soft tissue lesions AIS 1 had mean delta-v-values of 37.8 km/h. All the types of knee injuries AIS 2+ occurred with higher accident severity with mean delta-v of 46.1 km/h (tibia plateau fracture) until mean delta-v of 60.3 km/h for medial collateral ligament lesions.

It seems remarkable that for the occurrence of ligament injuries of the crucial and collateral structure of the knee higher load was required than for the bony fractures of the head of tibia, condylus and patella - mostly higher 50 km/h delta-v.

A comparison of airbag and non airbag cases shows a higher risk for knee injuries with airbag deployment (figure 17). Especially for higher delta-v > 30 km/h a significant higher portion of AIS 1 knee injuries can be found (by 25% higher for delta-v 31-40 km/h and 142% higher for delta-v 41-50 km/h). For AIS 2+ injuries a significant statement cannot be made due to the low number of cases.
CONCLUSIONS

This study showed that severe knee injuries for belted passenger car occupants are rather rare nowadays. From investigations at the sites of accidents by a scientific in-depth, on scene investigation in Hannover, a statistically representative percentage of only 0.4% of all injured car drivers was seen for accidents nowadays. In contrast to the situation of 10 years ago at the end of the 1980s to early 1990s, the risk for light (AIS 1) and severe knee injuries (AIS 2+) has decreased by 33%. AIS 1 soft tissue lesions of the knee are found in only 9.8% of the accidents involving passenger cars today.

The study also showed that knee injuries are not restricted to frontal collisions only, where they occur at 1.3% of the cases. They can be found in lateral collisions too, however nearly three times less frequent as in frontal collisions. Lateral impacts obviously involve an angled impact component transferred to the passenger compartment during the momentum exchange. Knee injuries are of note following multiple collisions, which are represent 30% of the accidents involving passenger cars, and thus occur frequently. 27.6% of people suffering from AIS 2+ knee injuries had been injured in multiple collisions.

The accident severity in the form of the change of the velocity “delta-v” due to the impact momentum exchange appears to be the most important influencing parameter in correlation with the occurrence of a knee injury and the severity to be expected by the intrusion of the compartment resulting in dashboard and footwall deformation. Especially at delta-v above 40 km/h there is a high probability for AIS 2+ knee injuries, which then increases significantly with the deformation of the compartment (intrusion). Nearly all ligament ruptures documented here occurred solely at higher delta-v values of more than 40 km/h. Patella fractures, fractures of the femur condylus and tendon ruptures could be observed at a delta-v of 20 km/h. Also, the accompanying injuries often associated with a knee impact, such as thigh, lower leg and foot as well as the pelvis significantly increases in combination and frequency with delta-v and intrusion. Thus severe knee injuries are interrelated in 32.7% of the cases with an intrusion of the passenger compartment, either in the footwell or in the area of the dashboard. With the findings of this study, the statement of Kuppa et al (2003) could not really be confirmed.

That is to say that there is a higher risk of AIS 2+ injury to the Knee-Thigh-Hip region in newer vehicle models equipped with airbags compared to older vehicles (before 1993). The presented study could find a higher risk for knee injury AIS 1, for AIS 2+ the numbers were too low for a significant conclusion. The accident severity and injury correlation that there should be a knee injury risk of 6%, for AIS 2+ in the delta-v range from 46 to 60 km/h could not be confirmed. This study pointed out a lower injury risk of only 3.5% only. Our study found 3.1% at delta-v 41-50 km/h. In our opinion the higher occurrence of knee injuries with airbag deployment may base on the higher load to the upper part of the body following in a forward relative movement of the lower extremities.
The classical dashboard injury that often occurred in the past very often with fractures of the acetabulum plus femur fracture and fracture of patella plus rupture of rear cruciate ligament is rare in accidents today. This is the most often the situation following a common mechanism of injury resulting in disruption of the posterior cruciate ligament (Sanders 2000). At a dashboard injury in the past in the unbelted situation, the tibia was forced posterior relative to the femur, the posterior cruciate ligament is tight and therefore a risk exists for disruption. Only one case with those injury patterns was found among the older cases from accidents during years 1985 to 1993. These results express the status of a good level of passive safety of cars.

**LITERATURE**


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