BIOMECHANICS OF UPPER LIMB INJURIES OF BELTED CAR DRIVERS AND ASSESSMENT OF AVOIDANCE

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ABSTRACT

Protection applicances in the car make driving increasingly safer. Due to this fact, fewer persons sustain injuries in the course of traffic accidents. It can be pointed out that the injury pattern of car passengers was visibly changed by the seat belt. With air bag a further protection can be awaited. It can be summarized that the current car safety did not protect all injuries. Most of the injuries are soft tissue lesions, fractures are seldom: 3.7% of injured belted car drivers suffered fractures of head, 5.7% thorax, 1.2% pelvis, 4.6% lower limbs and 3% upper limbs.

This study will explain the injury mechanisms of upper limb fractures and bring demands for car developments and dummy test work.

The data has been derived from traffic accidents documented by a scientific team at the Accident Research Unit of the Medical University Hannover / Germany, by order of the BAST.

3,200 belted car drivers could be analysed. A total of 179 persons with **upper limb fractures including joint lesions** were at disposal, documented during the years 1985 to 95 within a statistical random sample and weighting procedure.

It could be established that important for the resulting injuries, especially on the shoulder, are impulse direction and position of force transmission. Fractures of the shoulder were exposed to high collision severity. Isolated humerus fracture are incurred when a direct impact to the humerus region occurs mostly in lateral collisions.

The study demonstrates two different mechanisms for upper limb fractures:

1. direct impact with longitudinal and rotational load to hand, hand joint and lower arms resulting in a forward movement of the arm and rotational effects with injury risk for joints and lower arms
2. lateral collisions with load transmission to lateral parts of the arm resulting in injuries of the whole upper limb.

In the study the main influence factors for upper limb fractures are described and measures for avoidance discussed.

INJURIES FOR CAR DRIVERS involved in traffic accidents have been reduced, due to the fact that the forward movement of the body is restricted by the restraining function of the seat belt and the downward movement of the head is reduced and an impact softened by the air bag, which is implemented in the steering wheel.

In 735.000 cars involved in accidents with personal and extensive material damage in Germany in 1995 (StBA-1). 48,200 drivers suffered severe injuries (hospitalised treatment or killed respectively). This represents a percentage of only 6.6%. Serious injuries including fractures are relatively rare for car passengers .

The extremities, i.e. arms and legs are not specially protected. Only the restraining function of the safety belt effects a restricted forward movement of arms and legs and softens the impact intensity of the body. While leg injuries have been the subject of many publications in the past, analyses and avoidance concepts for arm injuries have hardly been carried out up to now.

It is the objective of this study to detect the mechanisms of arm fractures in order to work out effective prophylactic measures. The accident documentation of the Accident Research Unit at the Medical University Hannover[1] provide the basis due to their assessed extensive information about injury patterns, deformation characteristic and accident processes (Otte - 2).

BASIS OF THE STUDY

The basis of this study are 7,861 injured, belt-protected car drivers, collected in 9,380 traffic accidents with injured persons, documented from 1985 to 1995 by a scientific team consisting of medical staff and technicians in the greater vicinity of Hannover. 179 belt-protected car drivers suffered arm fractures. The definition "arm" includes the shoulder joint, upper arm, femur, elbow joint, spoke bones, radius, ulna, elbow, wrist and hand.

For the analysis of biomechanic mechanisms arm injuries were limited to fractures only. From the traumatic point of view, pure soft-tissue injuries are classified as minor injuries of severity degree AIS 1, and can be disregarded in this analysis.

Each injury is described, divided into type, localisation and severity in accordance with AIS (American Association for Automotive Medicine - 3).

For the accident investigations of Hannover a statistical spot-check plan is used which includes an annual random spot check of 1,000 traffic accidents with injured persons. These are compared annually with the official registered total number of all traffic accidents in the investigation area. Distorsions in the compared distributions are combined with weighting factors which are included in the data set. The percentages given with tables and diagrams are the result of this weighting procedure, the total numbers are not weighted. This way of a representative evaluation was made possible for the complex in question.

The very intensive in-depth investigations provide descriptions of vehicle deformation, impact points on car passengers and of the kinematic conduct of

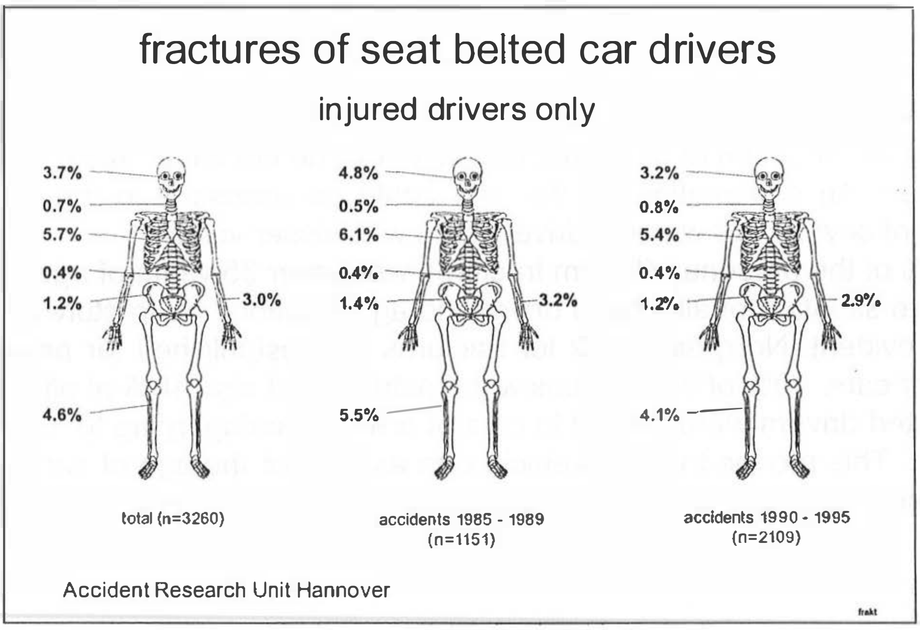
[1] carried out by order of Federal Highway Research Institute (BASt)

the vehicles, including the determination of impact speeds as well as the accident characteristics Delta-v and EES. Due to a detailed accident reconstruction based on the laws of physics and available software, the load endured by the passengers could be estimated with the help of the impulse angles and then be connected with the general injury situation.

FREQUENCY OF ARM INJURIES

It became evident that in case of the accident even bony injuries are very rare for belt-protected car drivers. Fig.1 shows the statistical percentage of persons with fractures to different body regions. The head, the thorax, arms and legs belong to the most frequently fractured body parts. The thorax represents the body region of belt-protected drivers most frequently traumatised by fractures in 5.7%. A comparison of accidents from the period of 1985 to1989 in relation to 1990 to 1995 clearly shows that the frequency of fractures for almost all body parts has been reduced, with the exception of the spine. The frequency of injuries of the lumbar vertebra region however has remained constant (0.4%) both before and after 1990. Fractures of the cervical vertebra in accidents after 1990 have become more frequent (0.8%), compared with 0.5% before1990 (fig. 1). Upper limb fractures could be observed in 3.2% of accidents before 1990 and a reduced number of 2.9% since 1990.

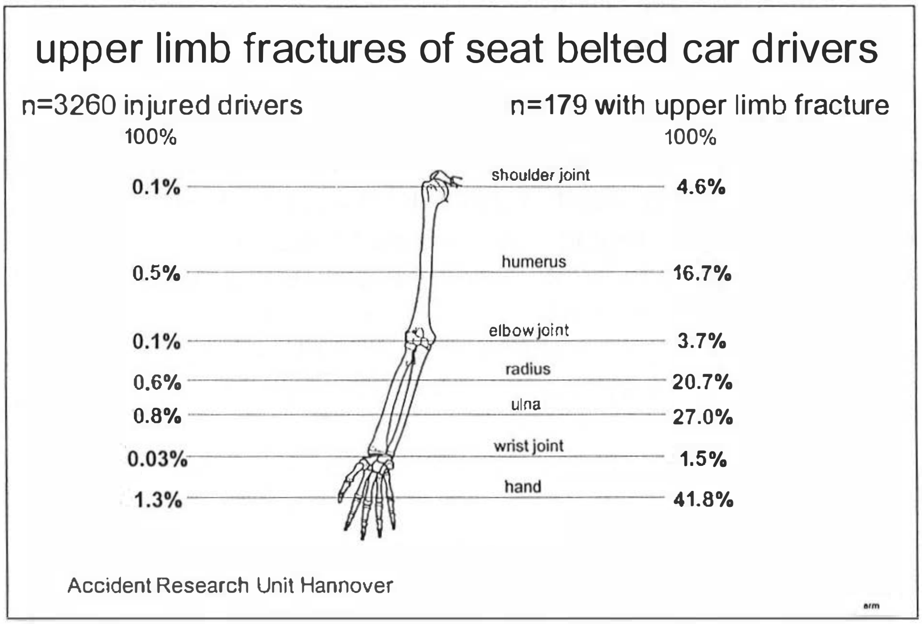
Fig. 1 Frequency of upper limb fractures to different locations (100% all persons each group



The long bones (humerus, radius and ulna) are the mainly traumatised regions (fig. 2). 16.7% of the persons with arm fractures had a broken humerus, 20.7% a broken radius and 27% a broken ulna. The hand bones were broken in 41.8% of the cases. 1.3% of all injured car drivers sustained hand fractures.

Fractures including those to the joint of the hand, the joint of the elbow and the shoulder are not frequent injuries for belt-protected car drivers (0.1%).

Fig. 2 Frequency of upper limb fractures for different locations (100% all person each collection)



Arm fractures are especially frequent in frontal collisions. 4.1% of the injured car drivers in frontal collisions and 2.5% of the impacted side seated drivers in lateral collisions occured fractures of arms. The impact-averted arm was also injured in some lateral collisions cases, where as the impact-directed arm remained uninjured. 32.8% of arm fractures were sustained by women, who in view of the situation to all injured drivers (41%) do not suffer these injuries quite so often. An explanation for this fact could be assessed in the often lesser accident severity for women, driven often with lesser velocity.

39% of the persons with arm fractures were over 35 years of age. Compared with the situation of all injured drivers no age influence for fracture risks seems to be evident. No greater risk for fractures was established for passengers of smaller cars. 40% of the persons with fractures, but also 40% of all injured belt-protected drivers were seated in cars of a weight category up to 1,000 kg curb weight. This proves that the vehicle size as well as the age of car passengers have no immediate influence on a fracture risk for the arms (tab. 1).

Tab. 1 Frequency of upper limb fractures related to mass of car, driver's age and gender (100% all persons each group)

injured seat belted car drivers

n=2557 (n=75 with upper limb fractures)

	injured seat belted car drivers	with upper limb fractures
total	**n=3260 (100%)**	**n=179 (100%)**
mass of car		
to 1000 kg	60,7%	60,3%
> 1000 kg	39,3%	39,7%
driver's age		
to 35 years	61,1%	61,1%
> 35 years	38,9%	38,9%
driver's sex		
male	59,0%	67,2%
female	41,0%	32,8%

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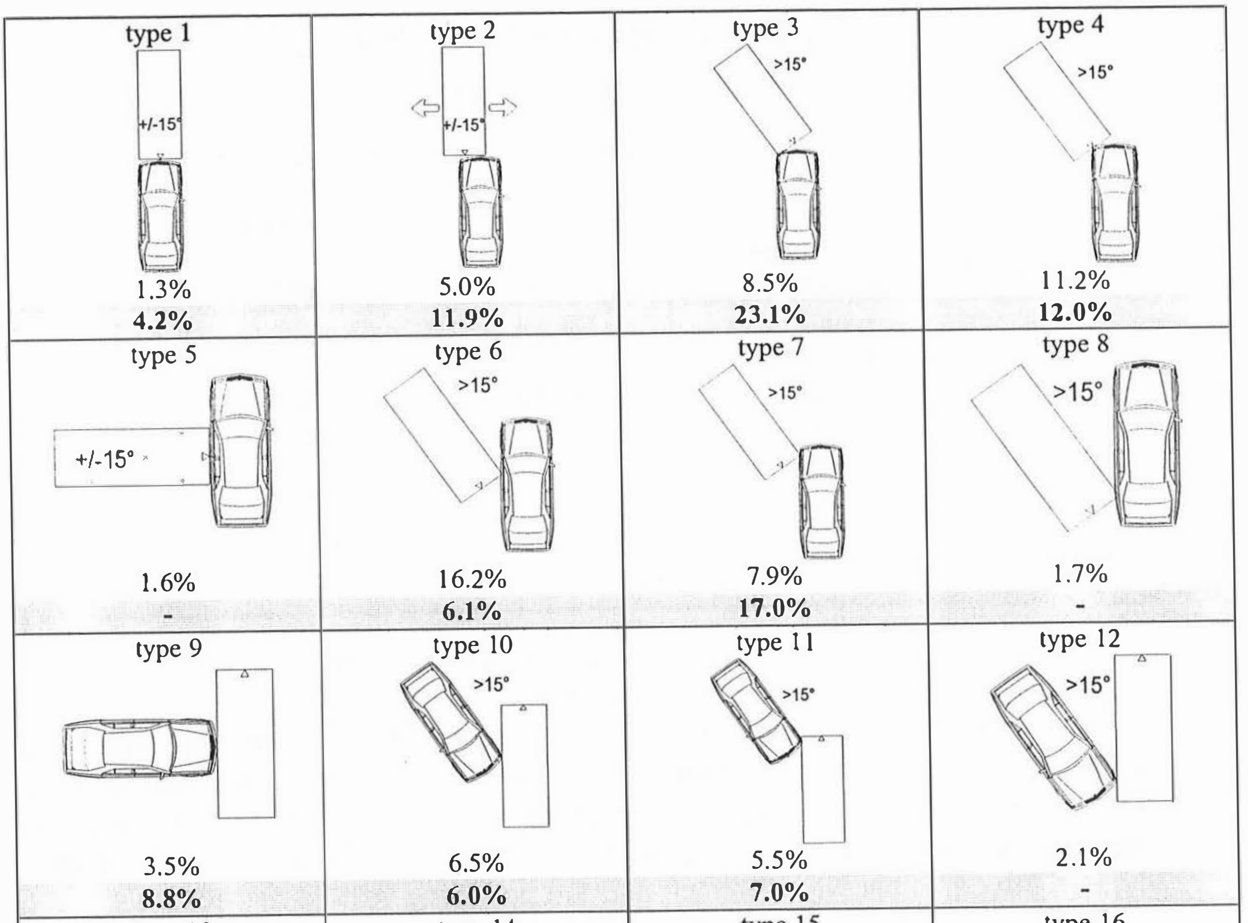
fig 3

The risk of arm fractures however mainly depends on the accident situation, such as the collision direction and accident severity.

For definition of collision types the impacts of cars are separated into collisions with other vehicles and collisions with objects, like pole, tree, wall etc. For these the collision types are defined for different impact area and the direction of force, rectangular (+/- 15 degrees) and oblique. In the following figures the car is shown as sketch and the opposing vehicle as rectangle.

Fractures of arms are occurred in frontal collision situations with other vehicles, so called „head-on offset-collisions“, and in lateral collisions under rectangular and oblique impact direction from the front (fig. 3 a).

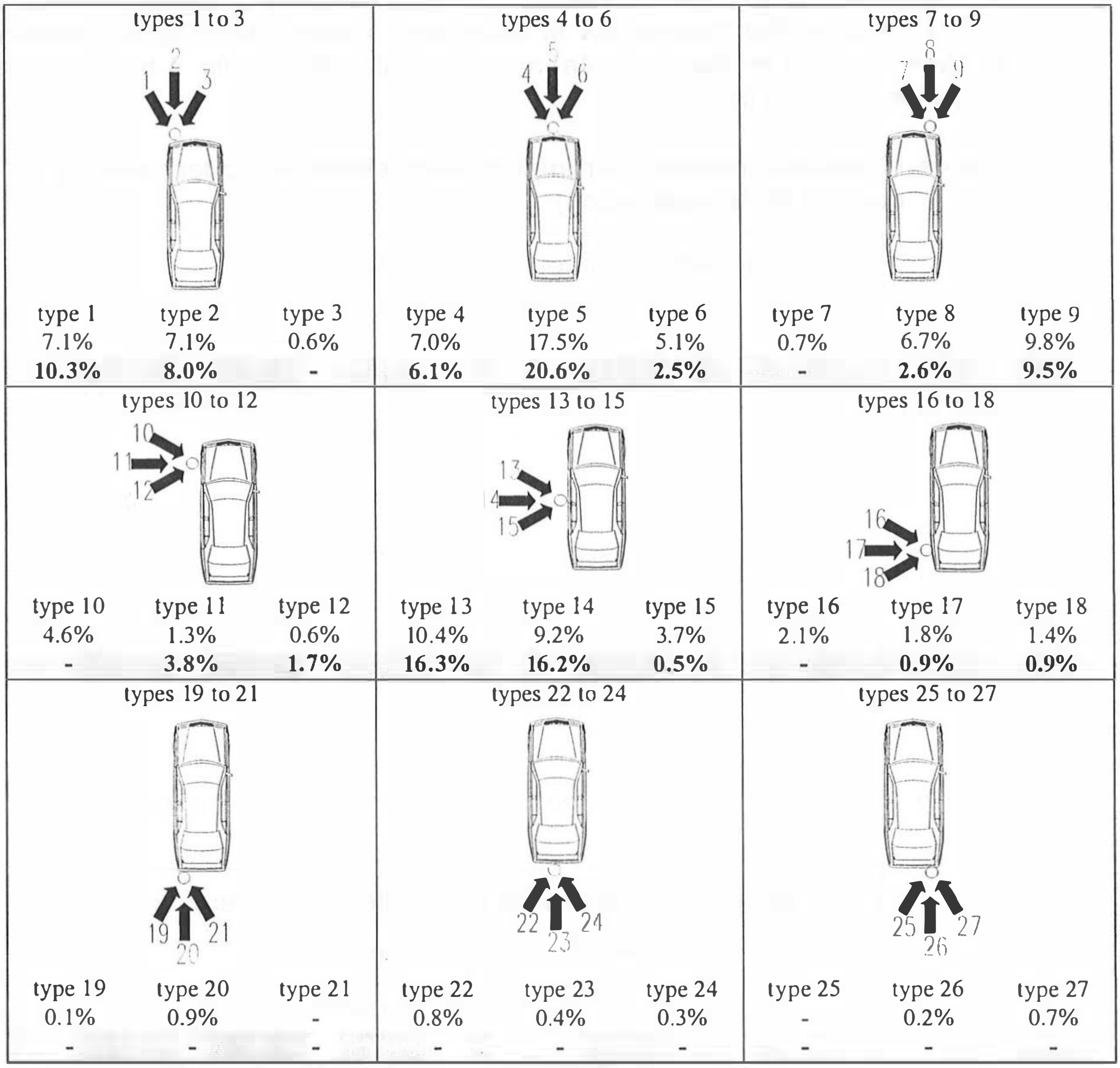
Fig. 3a Collision configurations for upper limb fractures in relation to all car accidents (100% all car drivers)



Upper row: all injured car drivers
Lower row: car driver with upper limb fracture

An impact of the car body with a tree/pole is resulting in an high intrusion and partly deformation of front and side structures (fig. 3 b).

Fig. 3b Collision configurations for upper limb fractures in relation to all collisions with tree/pole (100% all car drivers)



Upper row: all injured car drivers
Lower row: car driver with upper limb fracture

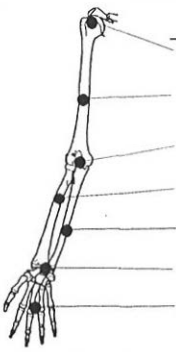
The main collision types are shown in fig. 3 a and b, those which could be seen as responsible for arm fractures are types 2, 3 and 7 for car to car accidents and types 1, 5 and 15 in car to pole collisions.

ACCIDENT SEVERITY AND INJURY MECHANISMS

The change of velocity, as a result of the collision Delta-v is a parameter for accident severity. This can retrospectively be established from the extent of deformation, from the brake-slinging distances of the car measured at the site of the accident, and the established collision and final position of vehicle. Figures 4 show the frequencies of upper limb fracture for different accident severities Delta-v in frontal (fig. 4a) and in lateral collisions (fig. 4 b) for drivers with sustained arm fractures.

Fig. 4a Upper limb fractures in **frontal** collision related to accident severity delta-v (100% each region)

upper limb fractures of seat belted car drivers
in frontal collision (n=77)



	delta-v [km/h]				
	to10	11-20	21-30	31-50	> 50
shoulder joint	-	-	-	-	100
humerus	-	-	-	54,9	45,1
elbow joint	-	-	-	39,4	60,6
radius	-	10,3	5,7	43,1	40,9
ulna	-	-	4,2	33,7	62,1
wrist joint	-	-	-	-	100
hand	-	2,7	45,6	36,5	15,3

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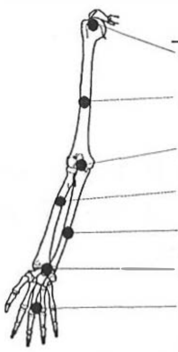
Fig. 4b Upper limb fractures in **side** collision related to accident severity delta-v (100% each region)

upper limb fractures of seat belted car drivers
in impact at left side (n=25)



	delta-v [km/h]				
	to10	11-20	21-30	31-50	> 50
shoulder joint	33,5	-	-	21,9	44,6
humerus	-	12,4	-	38,3	49,3
elbow joint	-	-	-	-	-
radius	-	-	-	51,9	48,1
ulna	-	-	-	33,2	66,8
wrist joint	-	-	-	-	-
hand	-	-	28	72	-

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Fractures of the arms occur frequently at high accident severities. 72% of the arm fractures occured at Delta-v values of more than 30 km/h. This is also shown by the cumulative frequency of delta-v values for seat belted car drivers with upper limb fractures (fig. 4 c).

Fig. 4c Occurrency of upper limb injuries related to accident severity delta-v (cumulative frequency for each collision type)

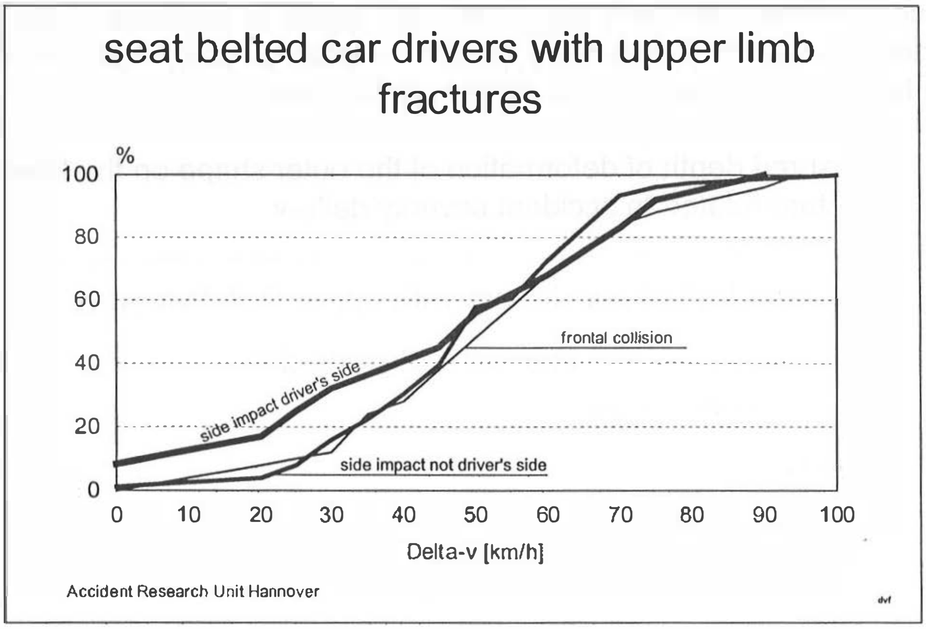
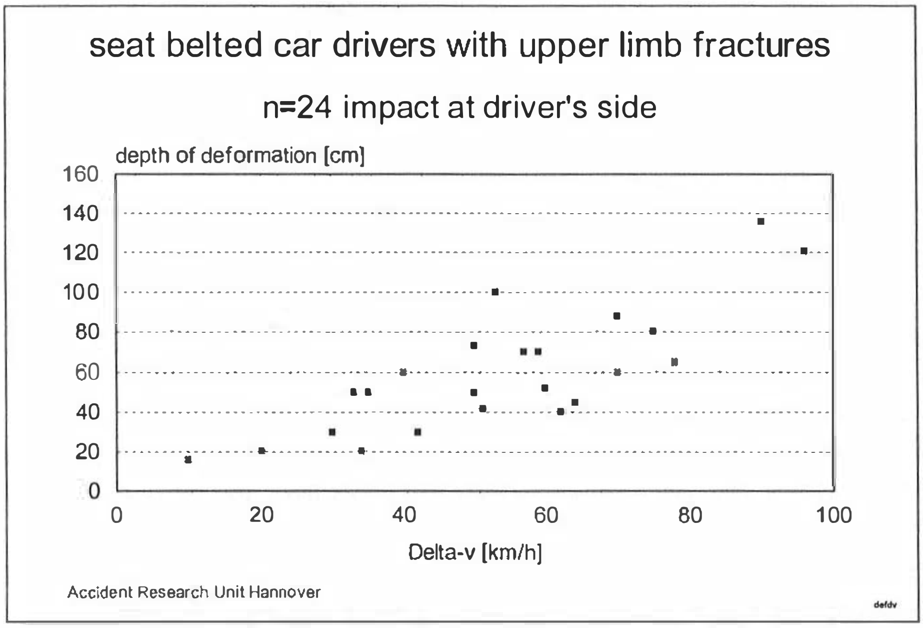


Fig. 4c clearly shows that hand fractures starts in **frontal collisions** already at less accident severities. Further that fractures are observed for Delta-v more than 10 km/h. 2.7% of drivers with arm fractures were observed at Delta-v values of 11 to 20 km/h. In speeds of 21 to 30 km/h 45.6% of the persons sustained hand fractures. At higher Delta-v values the wrist is involved, an indicator for more intensive load to the body. Injuries of hand and wrist were found exclusively in the accident severity region above 50 km/h. Fractures of the ulna were sustained to 62%, only in connection with accident severities of Delta-v above 50 km/h. Radius fractures are observed more frequently in lesser accident severities, above 10 km/h. As a rule, isolated arm fractures are localised to one of the two spoke bones, completed fractures of ulna together with radius were found in 7.7%. In accident severities of Delta-v above 30 km/h the upper arm is strained in such a way that fractures are caused. The frequency of fractures to the various arm regions in frontal collisions clearly demonstrates the supporting effect of the arm on which the hand as the weakest part, the impact load is mainly transferred via the radius bone. Therefore completed fractures (ulna and radius) are seldom observed in frontal collisions (5.4% of drivers with arm fractures). With increasing accident severity, the fracture risk for the arm travels from the forearm upward to the upper arm.

In a **lateral collision** (fig. 4b) a lesser injury probability exists for the hand up to Delta-v 20 km/h and for the wrist as well as for the ulna and radius up to

30 km/h. Fractures of ulna and radius are observed only in accident severity regions above 30 km/h. For the impact directed seated passenger, fractures of the upper arm, including the shoulder joint, already appear in the less accident severity region of up to 10 km/h. This clearly proves that the upper part of the body is moved inside the interior levels relatively toward the impact side in lateral collisions. The established loads are primarily transferred to the upper arm and shoulder region. The relatively free moving forearms and hands, at a distance from the main body mass, are only prone to fractures at higher levels of accident severity. This shows for side impact of cars, that the lower arm region had high mechanical load by intrusion of door (fig. 5).

Fig. 5 Measured depth of deformation of the outer shape on the lateral structure related to accident severity delta-v



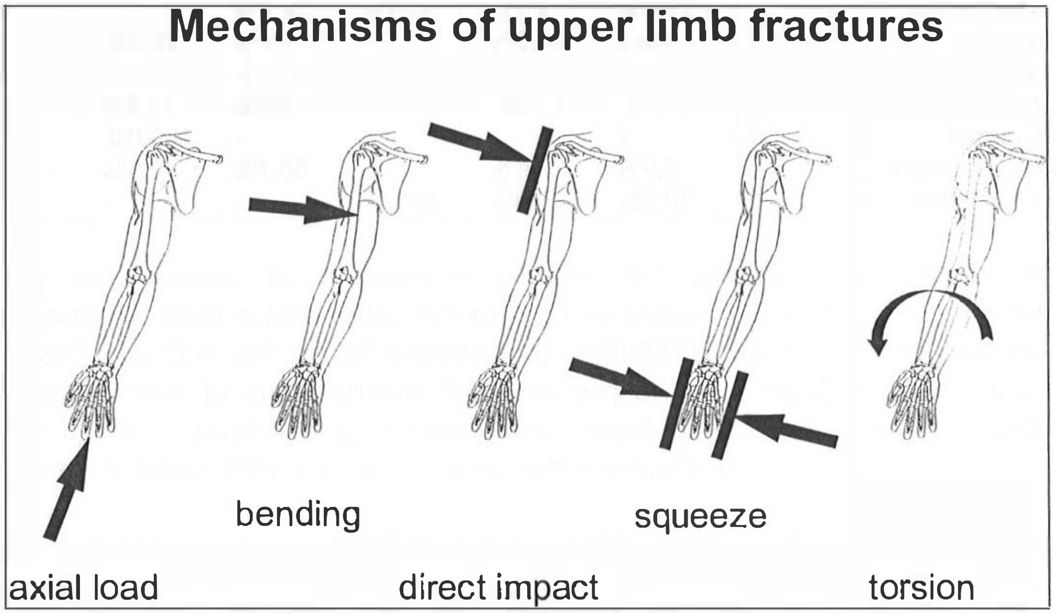
There is a bending mechanism often observed, resulting in complete fractures (ulna and radius).

Approximately 1/3 of all persons with arm fractures were injured in multiple collisions, i.e. the vehicle collided during the accident phase several times. In this situation, fractures are observed frequently on all parts of the arm for the involved belt-protected drivers, even in lesser accident severity.

The injury mechanisms were analysed within the framework of a detailed reconstruction case by case and looking for a possible body movement of the passengers, taken into consideration the result of arm fractures. For this purpose first of all the vehicle movement was established. The kinematics of the passengers was reconstructed by establishing the impact points inside the vehicle and the position and situation of the arm during the accident phase was estimated. The consequent body movements were established for persons with arm fractures.

Within the framework of the analysis, the **mechanisms** of n=94 cases were assessed in a detailed view of the types of fractures, which could be seen on the X-rays, and differentiated by bending, axial load, torsion, direct impact and squeeze mechanisms. Figure 6 shows the defined mechanisms responsible for arm fracture.

Fig. 6 Measured depth of deformation of the outer shape on the lateral structure related to accident severity delta-v



In 36.2% of the cases a direct impact and in 31.9% a bending was established as the main mechanisms. 21.3% of the mechanisms were axial loads (tab. 2). Other types of load are rare - squeeze was found in 8.5% and torsion in 2.1% of all arm fractures. For different locations there are different mechanisms most frequent. The mechanism bending is the most frequent one for elbow (60.0%) and wrist (72.2%), the axial load for shoulder (91.7%), the torsion for hand phalanges (60.0%), the direct impact for humerus shaft (36.4%), forearm shaft (63.2%) and hand metacarpal (66.7%) and the squeeze for hand carpal (100%).

Tab. 2 Mechanisms for upper limb fractures on different location (100% each loaction)

	total (n)	mechanism bending	axial load	torsion	direct impact	squeeze	others
total	94	31.9%	21.3%	2.1%	36.2%	8.5%	-
location							
shoulder	12	-	91.7%	-	8.3%	-	-
humerus shaft	11	36.4%	9.1%	18.1%	36.4%	-	-
elbow	10	60.0%	10.0%	-	10.0%	20.0%	-
forearm shaft	19	26.3%	-	-	63.2%	10.5%	-
wrist	18	72.2%	11.1%	-	5.6%	11.1%	-
hand carpal	1	-	-	-	-	100.0%	-
hand metacarpal	18	5.6%	22.1%	-	66.7%	5.6%	-
hand phalanges	5	20.0%	20.0%	60.0%	-	-	-

Within frontal collision, the relative movement of passengers in the compartment leads to a forward shifting of the arms and a main impact of the hands on the dashboard structures. Therefore a "direct impact" and "bending" as well as "axial load" are the predominant mechanisms of arm fractures in frontal collisions, most with hand and lower arm involved. Tab. 3 clearly demonstrates that the mechanism bending increases with greater values of delta-v.

In lateral collisions another mechanism can be seen often, this is "torsion" and in higher delta-v speed change during the collision "bending" is observed. Here a lateral movement of the arm, together with the upper body in combination with an additional influence of external deformations or intrusions respectively is influencing the injury occurrence. Most of arm fractures occur by bending and axial load.

In multiple collisions all of the different mechanisms can be seen, because there is a lot of different movements of the bodies and the arms.

Tab. 3 Mechanisms for different types of collision

	type of collision frontal delta-v		lateral delta-v		multiple delta-v	
	to 30	over 30	to 30	over 30	to 30	over 30
mechanism						
bending	20.0%	44.4%	-	36.4%	-	16.0%
axial load	20.0%	16.7%	50.0%	36.4%	36.4%	12.0%
torsion	-	-	50.0%	-	-	4.0%
direct impact	60.0%	36.1%	-	31.2%	31.2%	52.0%
squeeze	-	2.8%	-	-	36.4%	16.0%

Steering wheel and dashboard take first place among the injury-causing parts for arm fractures in frontal collisions. The forward movement of the arms to catch the of the upper body is the biomechanical explanation for the most injuries. Intrusions take in an important part for the anticipated fracture type in the Delta-v range of more than 30 km/h.

Lateral bending loads were often observed in connection with intrusion and lateral shifting of the seats, due to deformation of the floor structure. The centre of deformation was as a rule in the front and middle of the door region. The impact load was aligned from front to rear and a rectangular impulse transmission was observed.

CONCLUSION

The study demonstrates that fractures of the arms are sustained by 3% of all injured belt-protected car drivers. In comparison with the situation of legs (4.6%) a lesser injury risk exists. In today's accidents, arm fractures are less frequent than 5 years ago.

Hands, wrists and forearms are the focal point of interest in the injury localisation. Arm fractures occur in frontal and lateral collisions significantly above Delta-v values of 30 km/h only. The hands are the most injury exposed parts of the arms in view of the small and relatively weak bones . This may be an explanation for the fact that 42% of the drivers sustained hand fractures.

In view of the complicated course of therapy and difficulty to recover moving function of the wrist, fractures of the hand, the wrist and also the forearm are resulted often in long term consequences for the patient. It should therefore be the objective of engineers endeavouring to find measures for the reduction of the incidence of arm fractures of belt-protected car drivers.

While no significant parameters such as vehicle size (curb weight) or age factor of persons could be assigned, arm fractures were more frequent for men, due to the preferred higher driving speed and consequently higher accident severity. The study recommends the following concepts for the avoidance and reduction of arm fractures:

- padding of the dashboard
- padding of the door
- avoidance of frontal and lateral intrusion.
- relative large interior survival space

Beside frequency and injury severity the injury-causing interior parts and mechanisms of arm fractures have been established. Due to the fact that 36% of all fractures are sustained during a direct impact of the hand or arm, and 32% are caused by bending measures should mainly be taken to optimise energy absorption by padding the dashboard and the door.

The intrusion of the door from the side was established as an essential influence for arm fracture especially above delta-v values of more than 30 km/h. But also the intrusion from the front, leading to the shift of the A-pillar and dashboard backwards along the longitudinal axis, causing a reduction of space for the passengers. 64% of all arm fractures are sustained by additional intrusion. Delta-v and intrusion is working in correlation to each other.

Therefore intrusion should be avoided by reducing the accident severity or with more rigid compartment structures.

The off-set collision of the car, with partly overlapping of the vehicle front and the rectangular and oblique lateral impact against the passenger compartment of the car represent the essential collision types for arm fractures. For this reason, the regular test conditions for frontal and lateral collisions, in accordance with EU directive 70/156/EEC, to be carried out from 1998 on in Europe could help for avoiding arm fractures on one hand, but on the others there could be the need to include a criteria for arm encumbrance later on.

The often discussed test proposal of a pole impact (Otte - 4, Bröcking - 5, Langwieder - 6) should recalled again under the demand for the avoidance of arm fractures, especially for the avoidance of intrusion of the small pole in the lateral door structure.

REFERENCES:

(1) StBA: Statistical data of traffic accidents in Germany 1995, Stat. Bundesamt Wiesbaden, Fachserie P, Reihe 7, Verlag Metzler-Poeschel, 1996

(2) Otte, D.: The Accident Research Unit Hannover as Example for Importance and Benefit of Existing In Depth Investigations, SAE-Paper No. 940712, Proc. International SAE Congress, Detroit/USA, 1994

(3) American Association for Automotive Medicine: The Abbreviated Injury Scale AIS, Revision 90, Morton Grove, Illinois/USA, 1990

(4) Otte, D.: Assessment of Measures Reducing Residual Severe and Fatal Injuries MAIS 3+ of Car Occupant, Paper No. 96-S4-W-18 - Vortrag und Proc. 15th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Melbourne/ Australia, Mai 1996

(5) Bröcking, J.: Der Pfahlanprall - HDT-Tagung Essen 1997

(6) Langwieder, K.: Realitätsbezogene Crashtests - eine Grundlage für mehr Sicherheit von Pkw, Tagung Crash-Tech 96, TÜV Bayern, München - 15. Oktober 1997