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Foot Fractures in Restrained Front Seat Car Occupants: A Long-term Study Over Twenty-three Years

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Objectives: To analyze the mechanism of injury for foot and ankle fractures resulting from automobile accidents to create a basis for developing an improved design for protection.
Design: Retrospective.
Setting: Level I trauma center with accident research unit.
Patients: Automobile accident reports and medical records of individuals injured in the accidents.
Main Outcome Measurements: Technical indicators (collision type, impulse angle, δv, and extent of vehicle deformation) and clinical data (injury location and severity [abbreviated injury scale and injury severity score] and long-term outcome).
Results: From 1973 to 1996, 15,559 car accidents were analyzed. Two hundred sixty-one front seat occupants sustained fractures of the foot and ankle (ankle, 41 percent; forefoot, 29 percent; midfoot, 20 percent; and hindfoot, 10 percent). Seventy-five percent of the fractures were classified abbreviated injury scale$_{foot}$ 2. The incidence, location, and abbreviated injury scale$_{foot}$ category of fractures were similar between driver (n = 210) and front seat passenger (n = 51). Fifty percent of the fractures occurred in head-on collisions and 34 percent occurred in accidents with multiple collisions. The δv ranged in 82 percent of car crashes between fifteen and sixty kilometers per hour. The δv and extent of foot compartment deformation correlated with the abbreviated injury scale. During our investigation, δv increased; the injury severity score decreased; and the extent of deformation did not differ significantly.
Conclusions: Although overall car passenger safety has improved, the relative incidence of foot and ankle fractures has increased. Comparing drivers and front seat passengers, the foot pedals, steering wheel, or the asymmetric design of the dashboard did not influence injury incidence, mechanism, or severity. Foot fractures are mainly caused by the foot compartment deformation in head-on collisions, and therefore improvements in foot compartments are essential for fracture prevention.
Key Words: Car crash, Foot fracture, Injury mechanism, Long-term outcome, Prevention.

Although improved passenger protection by means of safety belts and airbags led to decreased frequency of injuries related to car crashes, foot and ankle injuries have increased in frequency and severity (7,12,13,31). In motor vehicles, extremities are not specifically protected. However, the restraining effect of safety belts and the cushioning effect of airbags have lowered the collision impact for extremities (7). Corresponding with our observations in a Level I trauma center, the long-term outcome of foot fractures in car crashes often leads to a high degree of impairment (2,3,10,18,19,25,26). Initially, the frequency of fractures of the foot and ankle region in restrained car drivers and front seat passengers was evaluated. The injury origin, type, and extent were then evaluated. Based on a reported average car occupancy of 1.3 and a seatbelt usage of front occupants greater than 90 percent in Germany in recent years, only restrained front seat occupants were considered as a representative sample (20). We intended to determine the differences between drivers and front passengers. The aim of this study was to analyze the mechanism of injury of foot and ankle fractures caused by automobile crashes to create a basis for developing an improved design for protection.

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MATERIALS AND METHODS

In a statistical retrospective analysis of car collision files from 1973 to 1996, the incidence and mechanism of foot and ankle fractures in restrained front seat occupants was examined. The accident files had been prepared by scientific teams of the Accident Research Unit. The teams had been informed through police dispatch and quickly arrived at the accident scenes in their own squad vehicles. In Hannover, Germany and the surrounding rural district, approximately 6,000 automobile accidents with passenger injuries occur each year. Approximately 1,000 (17 percent) of these collisions have been documented annually since 1988. This was done according to a statistical sample design plan. From 1973 to 1987, an average of 300 vehicular collisions per year were evaluated. One exception was when the Accident Research Unit moved to new offices in 1979 and analyzed only twenty-four accidents. In addition to technical indications and an evaluation of the damage to the car, the files also included medical records outlining the types and severity of the injuries to the occupants. Seatbelt use was determined by history or assessment of the injury pattern.

The first medical institution providing care for the injured people documented the diagnosis and types of injury. Pictures of the vehicular collision scene and the inside and outside of the cars and the relevant radiographs were collected by the staff of the Accident Research Unit. Through this database, we were able to reconstruct the injury mechanisms in detail. This reconstruction was performed by the staff of the Accident Research Unit under the direction of the technical author (D.O.). The injury severity was classified with the abbreviated injury scale (AIS) (Table 1) for the foot and the injury severity score (ISS) (1,5). These classifications were performed by the staff of the Accident Research Unit. To estimate the relevance of the improvements of the passive car safety, accidents occurring from January 1, 1973 to December 31, 1989 (Group I) and from January 1, 1990 and December 31, 1996 (Group II) were compared. For the statistical analyses, *t*, Pearson, chi-square, linear trend, or Kruskal-Wallis tests were used.

RESULTS

From 1973 to 1996, 15,559 motor vehicle accidents with 21,799 involved vehicle car occupants were evaluated in the area of Hannover, Germany. In these accidents, 8,053 restrained front seat occupants (car drivers and front seat passengers) were injured. A total of 2,191 (27.2 percent) of those sustained a fracture and 261 (3.2 percent) sustained a fracture of the foot. Two hundred ten (80.5 percent) were drivers and fifty-one (19.5 percent) were front seat passengers. During the time of the study, the number of front seat occupants with fractures of the foot region increased from two to five per year in the 1970s and early 1980s to twenty per year in the late 1980s and 1990s. In the same time, however, the number of the evaluated accidents increased by 600 percent from 200 to more than 1,200 per year. The proportion of the front seat occupants with fractures of the foot in relation to the number of the evaluated accidents slightly decreased over the study period (Fig. 1). A peak in the relative incidence of foot fractures occurred in 1979, when only twenty-four accidents were evaluated. A large decrease was observed between 1989 and 1990 (Group I, 6,378 evaluated accidents, 139 (2.18) front seat occupants with fractures of the foot region; Group II, 9,181 evaluated accidents, 122 (1.33 percent) front seat occupants with fractures of the foot region). Of the front seat occupants with fractures of the foot or ankle, 1.9 percent (n = 5) were protected by airbags, and the airbags were deployed in only two crashes.

The mean age of front seat occupants at the time of the accident was thirty years (range 3 to 83 years). Men (n = 176) were affected twice as often as women (n = 85), although 41 percent of the injured were female in total. Twenty-three (9 percent) individuals sustained fatal injuries. In 60 percent of the front seat occupants, the driver's side limb was affected (drivers, 64 percent; front seat passengers, 56 percent; chi-square test, p = 0.041). Twenty-six (10 percent) sustained bilateral foot fractures (drivers, n = 22 [10.5 percent]; front seat passengers, n = 4 [7.8 percent]). Among the 511 single fractures of the foot region in front seat occupants, the ankle was affected most often (41 percent), followed by the forefoot (distal to Lisfranc's joint) (29 percent), midfoot (20 percent), and hindfoot (between ankle and Chopart's joint) (10 percent). No significant differences in the fracture location distribution between drivers and front seat passengers were noted (chi-square test, p = 0.416) (Table 2). Fifteen percent were open fractures, and they were nearly equally distributed between drivers and front seat passengers. In front seat occupants, 75 percent of the foot fractures were classified as AIS 2, 18 percent as AIS 1, and 8 percent as AIS 3, with almost equal distribution in

TABLE 1. *Abbreviated injury scale (AIS) for the foot*

AIS 1: fracture of toes and minor to moderate soft tissue injuries
AIS 2: all fractures of the foot region, except severe dislocation- or comminuted fractures (compare AIS 3), and severe soft tissue injuries
AIS 3: dislocation fractures of the ankle with posterior Volkmann triangle, Chopart-Lisfranc dislocation-fractures, most severe soft tissue injury, and traumatic amputation

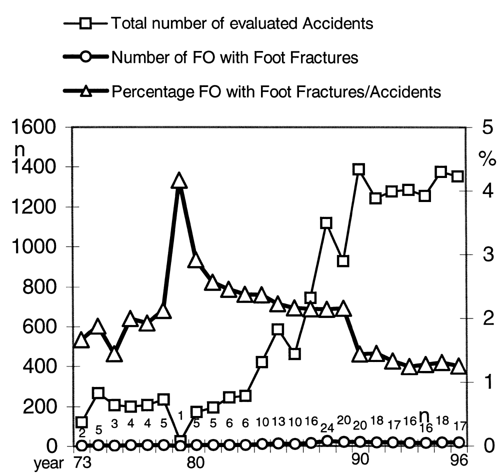

FIG. 1. The number and percentage of front seat occupants (n = 261) with fractures of the foot region.

TABLE 2. *Statistical analysis of front-seat occupants with fractures of the foot region*

	Front-seat occupants (n = 261)	Drivers (n = 210)	Front-seat passengers (n = 51)	Statistical difference drivers and front-seat passengers
Age (yr)	35.21 ± 16.18	35.67 ± 14.9	34.84 ± 24.5	t test, p = 0.265
Gender, M:F	2.14:1	2.87:1	1.65:1	chi square test, p = 0.128
Side, lateral/medial (%)	60/40	62/38	57/43	chi square test, p = 0.089
Location (%)	41/10/20/29	41/9/20/30	43/13/18/26	chi square test, p = 0.416
AIS of the foot (%)	18/75/7	17/74/9	21/73/6	linear trend test, p = 0.591
ISS	3.3 ± 11.7	3.4 ± 9.7	3.2 ± 21.4	Kruskal-Wallis test, p = 0.634
Type of collision (%)	50/12/0.8/0.4/37	49/13/1/1/36	52/10/0/0/38	linear trend test, p = 0.749
δv	39.7 ± 25.1	40.5 ± 19.6	38.2 ± 28.3	t test, p = 0.356
Extent of deformation (%)	24/26/25/26	23/26/25/26	25/25/25/25	linear trend test, p = 0.745

Age, mean age ± standard deviation. Side, lateral or medial limb in relation to the vehicle in percent; lateral is left for drivers and right for front-seat passengers. Location, ankle/hindfoot/midfoot/forefoot in percent. AIS of the foot, AIS 1/AIS 2/AIS 3 in percent. ISS, mean ISS ± standard deviation. Type of collision, head-on/side/rear-end/rollover/multiple in percent. δv, mean δv in kilometers per hour ± standard deviation. Extent of deformation, none/minor/moderate/severe in percent. Significance, *p = 0.05; **p = 0.01; ***$p \leqslant 0.001$.

AIS, abbreviated injury scale; ISS, injury severity score.

drivers and front seat passengers. The ISS did not differ considerably between drivers and front seat passengers, with mean values of 3.4 and 3.2 (Table 2). Groups I and II showed no significant differences in age, gender, seating position, injury side, and AIS. In Group I, the fractures were located in the forefoot in 45 percent of cases, whereas 47 percent of Group II had fractures of the ankle region (location distribution difference, chi-square test, p = 0.050). The ISS was higher in Group I (Kruskal-Wallis test, $p < 0.001$) (Table 3).

The long-term outcome (7 to 23 years after injury) was evaluated in front seat occupants from Group I in 1996. In many cases, the ability to work was influenced mainly by the foot injuries (Fig. 2). Other causes for a significant disability in the long-term were mainly injuries to the head and pelvis. Among the foot injuries, the highest degree of impairment was caused by fractures of the midfoot (n = 28; mean limitation of working ability caused by the foot fracture, 23 percent; difference to

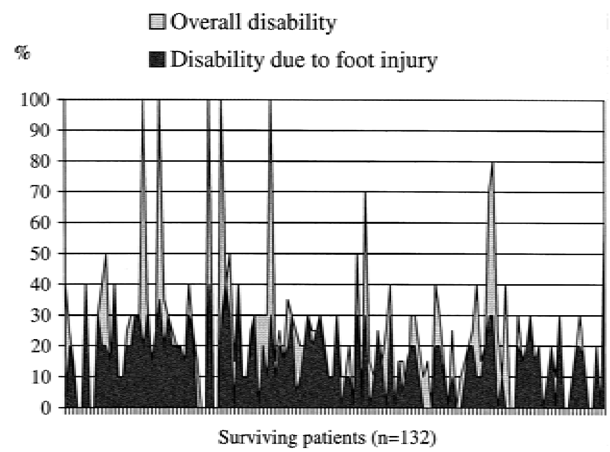

FIG. 2. Entire limitation of working ability and limitation of working ability only caused by the foot injury of the surviving front seat occupants with fractures of the foot region sustained between 1973 and 1989 (Group I), seven to twenty-three years after injury.

TABLE 3. *Statistical analysis of front-seat occupants with fractures of the foot region*

	Total group 1973–1996 (n = 261)	Group I 1973–1989 (n = 139)	Group II 1990–1996 (n = 122)	Statistical difference between Groups I and II
Age (yr)	35.21 ± 16.18	34.75 ± 14.9	35.73 ± 17.5	t test, p = 0.637
Gender, M:F	2.14:1	2.03:1	2.25:1	chi square test, p = 0.345
Drivers/front-seat passengers (%)	81/19	81/19	80/20	chi square test, p = 0.842
Side, lateral/medial (%)	60/40	64/36	56/44	chi square test, p = 0.235
Location*	41/10/20/29	36/6/12/45	47/15/28/10	chi square test, p = 0.050
AIS of the foot (%)	18/75/7	16/75/9	19/74/6	linear trend test, p = 0.378
ISS***	3.3 ± 11.7	3.7 ± 12.3	2.8 ± 11.7	Kruskal-Wallis test, $p < 0.001$
Impulse angle	168° ± 41.8°	172° ± 39.8°	164° ± 45.2°	linear trend test, p = 0.731
Type of collision	50/12/0.8/0.4/37	48/12/0/1/39	59/9/2/0/36	linear trend test, p = 0.265
δv*	39.7 ± 25.1	37.2 ± 24.7	42.6 ± 25.3	t test, p = 0.05
Extent of deformation (%)	24/26/25/26	22/25/26/27	26/27/23/24	linear trend test, p = 0.241

Age, mean age ± standard deviation. Side, lateral or medial limb in relation to the vehicle in percent; lateral is left for drivers and right for front-seat passengers. Location, ankle/hindfoot/midfoot/forefoot in percent. AIS of the foot, AIS 1/AIS 2/AIS 3 in percent. ISS, mean ISS ± standard deviation. Impulse angle, mean impulse angle in degrees ± standard deviation. Type of collision, head-on/side/rear-end/rollover/multiple in percent. δv, mean δv in kilometers per hour ± standard deviation. Extent of deformation, none/minor/moderate/severe in percent. Significance, *p = 0.05; **p = 0.01; ***$p \leqslant 0.001$.

AIS, abbreviated injury score; ISS, injury severity scale.

nonmidfoot fractures, 0 to 35 percent; linear trend test, $p = 0.05$).

To evaluate the origin of the injuries, the impulse angle, extent of the passenger cell deformation, deformation direction, and effect of the crash on the occupants were analyzed. The actual impact (most severe impact in multiple collisions) of the vehicle correlates with the impulse angle; under this direction (angle) the forces affect the vehicle and its occupants. The impulse angle or direction of force does not exactly correspond to the type of collision, although a high correlation for most crashes exists. The impulse angles were classified into twelve different groups. The 0-degree or 360-degree group corresponds to an impact directed from the front to the rear. The impulse angles could be determined in 95 percent ($n = 248$) of the crashes of front seat occupants with fractures of the foot region (drivers, 95 percent [$n = 200$]; front seat passengers, 94 percent [$n = 48$]). In drivers ($n = 150$) and front seat passengers ($n = 36$), the impulse angles ranged in 75 percent in the 30-degree, 0-degree, or 330-degree (−330-degree, −360-degree, or −30-degree) groups. This corresponds to an impact vector that affected the vehicle from the front to the rear. In 11 percent ($n = 22$) and 21 percent ($n = 10$) of the crashes, impacts directed from the same side in relation to the seating position toward the interior of the vehicle occurred (drivers, 60-degree, 90-degree, or 120-degree [−300-degree, −270-degree, or −240-degree] groups; front seat passengers, 240-degree, 270-degree, or 300-degree [−120-degree, −90-degree, or −60-degree]) groups (Fig. 3). No statistical difference in the distribution of the impulse angles was found between Groups I and II (Table 3).

The type of collision is determined by the location of the impact. Fifty-percent of the foot fractures occurred in head-on collisions and 34 percent occurred in accidents with multiple, including head-on, collisions. Side impacts (12 percent) were infrequent. Rear-end collisions caused foot fractures in two cases and rollovers in only one case. In the total group of all 15,559 evaluated accidents, head-on collisions (36 percent) and accidents with multiple collisions (36 percent) were more frequent than side impacts (17.7 percent), rear-end collisions (6.7 percent), and rollovers (1.5 percent). Drivers, front seat passengers, and Groups I and II did not differ in the distribution of the type of collision (Tables 2, 3).

A parameter for the seriousness of the car crash is the change of velocity or δv as a consequence of the collision. This can be determined retrospectively from the extent of the deformation, the breaking and skidding distances measured at the scene, and the collision location and the final positions of the cars.

The δv ranged in 82 percent (n = 213) of front seat occupants between fifteen and sixty kilometers per hour (drivers, 82 percent [$n = 173$]; front seat passengers, 78 percent [$n = 40$]). The extent of foot compartment deformation was classified into four groups: none, minor, moderate, and severe. These four groups were filled equally without significant changes of that distribution in drivers, front seat passengers, and Groups I and II. The extent of foot compartment deformation increased when δv was greater than fifteen kilometers per hour (Fig. 4). In front seat occupants, the location of the foot compartment deformation was frontal in 34 percent and frontolateral in 28 percent. No correlation was found between location of deformation and injury severity (AIS) in any of the groups, that is, front seat occupants, drivers, front seat passengers, Group I, or Group II. The δv and extent of deformation correlated with the AIS_{foot} in all groups (front seat occupants, Pearson, δv, Group I $r = 0.78$, Group II $r = 0.81$; extent of deformation, Group I $r = 0.82$, Group II $r = 0.79$) (Fig. 5). Group I showed a higher total injury severity (mean ISS, 3.7 ± 12.3) than Group II (mean ISS 2.8 ± 11.7, Kruskal-Wallis test, $p < 0.001$). The extent of deformation did not significantly differ, although the δv was higher in Group II (mean δv

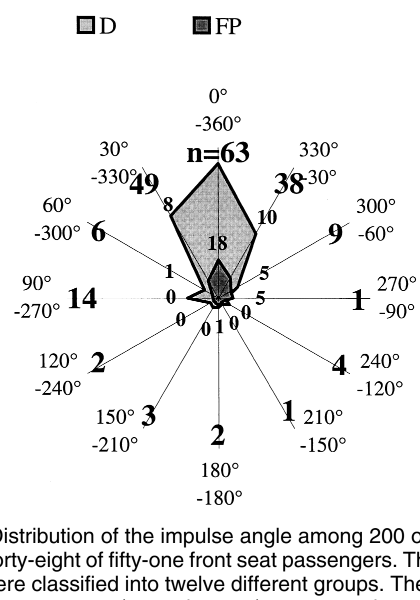

FIG. 3. Distribution of the impulse angle among 200 of 210 drivers and forty-eight of fifty-one front seat passengers. The impulse angles were classified into twelve different groups. The 0-degree or 360-degree group (± 15 degrees) corresponds to an impact directed from the front to the back. The figure shows the numbers of crashes in each group (drivers, larger numbers; front seat passengers, smaller numbers).

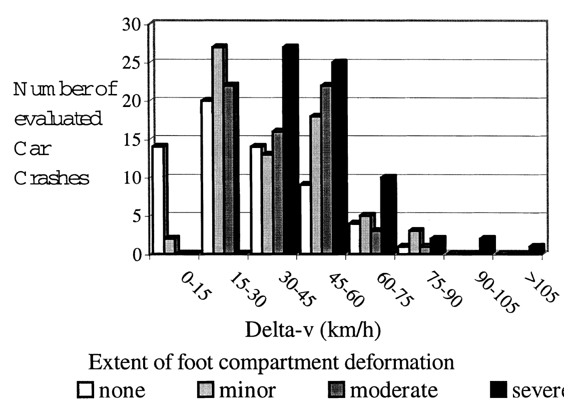

FIG. 4. Extent of foot compartment deformation and δv in 261 front seat occupants with fractures of the foot region.

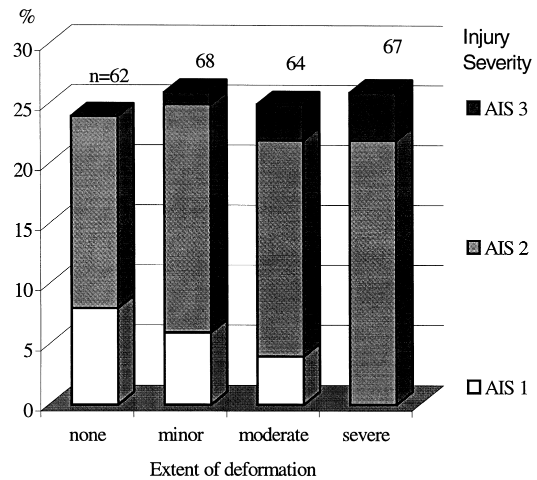

FIG. 5. Abbreviated injury scale of the foot and extent of deformation in 261 front seat occupants with fractures of the foot region.

Group I, 37.2 kilometers per hour; Group II, 42.6 kilometers per hour; *t* test, $p = 0.05$) (Table 3).

DISCUSSION

Although a considerable increase in automobile accidents and automobile crash injuries occurred in the 1950s, 1960s, and 1970s, a reduction in injuries has been documented in more recent decades. This is possibly a result of seatbelt laws despite the ever-increasing accident rate (30). Because of legislation in Germany, seatbelt use in car occupants is an important content of every traffic police protocol, because unrestrained occupants may lose their insurance coverage. Therefore, seatbelt use is documented in each vehicular collision. Based on these strict rules, more than 90 percent of automobile occupants in Germany wear seatbelts (22). Passenger safety was also improved considerably by stiffening the vehicle structure and by incorporating airbags (16,28, 31). These improvements have mostly reduced injuries to the head, neck, torso, and upper extremity (13). During this time, the absolute number of fractures of the foot region increased slightly but remained almost the same proportionally to the number of accidents and injury severity (7,17). For car occupants, fractures of the foot develop through different mechanisms (8,11,24). A combination of the front seat position and a head-on collision was described as contributing factors (9,14,15,23). In Germany a car occupancy of 1.3 for recent years has been reported, meaning that most cars are occupied only by the driver and a front seat passenger (21). Therefore, it is appropriate to limit a study only to front seat occupants as a representative sample. The unilateral pedals and steering wheel are the elementary differences between drivers and front seat passengers. Whether the pedals, steering wheel, or asymmetric design of the dashboard have an effect on the mechanism or extent of the injury has not been determined. In this regard, a comparison between drivers and front seat passengers may be valuable. Furthermore, it is useful to evaluate only restrained occupants because the protective effect of the safety belt is evident and number of restrained occupants is now more than 90 percent in the geographic area investigated (14,15,21,28,30). During the time of the investigation, each registered car was equipped with automatic three-point shoulder and lap safety belts for the front seats coming from the B pillar. Thus, the drivers with fractures of the foot region were similarly protected by safety belts. Based on this standardized seatbelt use, the injury mechanisms could be determined more reliably. Although most cars manufactured today are equipped with airbags (12), only 1.9 percent ($n = 5$) of the injured with fractures of the foot or ankle were airbag protected and only two of those airbags were released during the crashes in this study. This is based on the period of the evaluation between 1973 and 1996. The percentage of the airbag-equipped cars in the geographic area investigated was 0 percent at the beginning of the study and approximately 4 percent at its end. Because of the low proportion of airbag-protected injured occupants, no comparison with the entire collective could be performed. Even with a matched pair procedure, no comparison was possible because there were not enough injured occupants with airbags available to match.

The problem of reporter biases was minimized by taking photographs of the accident scenes and the inside and outside of the involved cars. In addition, photographs of the clinical aspects of the injuries and the relevant radiographs and computed tomography scans were collected. The technical classification was performed because of a standardized protocol under responsibility of the technical author (D.O.). Misclassification of injuries and fracture patterns was appreciated as a main problem, and therefore, two orthopaedic surgeons (M.R., E.S.) performed the classifications independently. Each case with any deviation in one or more classifications ($n = 10$) was discussed and classified again by both surgeons together. With this study design, an objective, reliable, and reproducible evaluation was obtained.

In our study, the percentage of registered injured occupants with fractures of the foot and ankle in relation to the number of evaluated accidents decreased slightly during our observation period (1973 to 1996). However, the improvements in passive safety that were effective in the period of the evaluation for injuries to the head, neck, thorax, and pelvis did not lead to a considerable reduction in foot fractures (13). In addition, the injury severity (AIS_{foot}) did not significantly differ between the injured before 1990 (Group I) and later (Group II). In our study, 50 percent of the foot fractures occurred in head-on collisions and 34 percent occurred in accidents with multiple, including head-on, collisions. The δv ranged in 82 percent of the cases between fifteen and sixty kilometers per hour, and the extent of deformation correlated highly with the δv. Seventy percent of the foot fractures were located at the ankle and forefoot. Surprisingly, drivers and front seat passengers showed a similar distribution of the fracture location. Furthermore, drivers and front seat passengers did not show any other differences, including injury severity (AIS_{foot} and ISS) and crash parameters (type of collision, δv, and extent of foot compartment deformation). Therefore, there was no effect of the pedals, steering wheel, or asymmetric design of the dashboard on the mechanism or extent of the injury for this group of patients.

Moderate injury severity (AIS_{foot} 2) predominated with 75 percent of the cases. The δv and extent of deformation correlated with the AIS_{foot}. The main factor causing foot fractures AIS_{foot} 2+ was foot compartment deformation. The extent of deformation remained the same during the time of our investigation, although the crash severity (δv) increased in the same time (δv higher in Group II). This tendency of increasing car safety reflects the decreasing ISS in the last decades (ISS lower in Group II). Nevertheless, the severity of foot fractures (AIS_{foot}) remained the same. Therefore, a further increase of foot compartment stability would be essential for prevention. The distribution of the fracture location changed over the time of our investigation (comparing Group I and II). Whereas the forefoot was affected most frequently in accidents before 1990 (Group I), we found mostly fractures of the ankle region later on (Group II). This change is caused by improvements of the passenger protection and by increasing crash severity (δv). At the same time that the improving stability of the passenger cell and foot compartment led to a decreasing percentage of forefoot fractures in relation to the other foot regions, the ankle with a mostly indirect injury mechanism was affected in a higher percentage of injuries. The foot fractures, especially those in combination with other injuries, were frequently not recognized during the primary examination and therefore were underestimated (2,4,10,18, 25). The complication percentage is high and adequate treatment is difficult (27,32). Midfoot fractures particularly have a high rate of late morbidity (6,19,29). In long-term outcome there was a high degree of impairment caused by foot fractures, especially midfoot fractures.

Although passenger protection in vehicles is improving, the relative incidence of foot and ankle fractures is increasing. Therefore, the prevention of these fractures in the future is important. In comparing drivers and front passengers, the pedals, steering wheel, or asymmetric design of the dashboard do not influence the injury incidence, mechanism, or severity. Foot fractures are mostly caused by foot compartment deformation in frontal collisions without a difference in the incidence of fractures of the foot in light and heavy cars. A further increase of foot compartment stability would be essential for prevention of these injuries.

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