TECHNICAL PARAMETERS AND MECHANISMS FOR THE INJURY RISK OF THE KNEE JOINT OF VULNERABLE ROAD USERS IMPACTED BY CARS IN ROAD TRAFFIC ACCIDENTS

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ABSTRACT

The paper describes the injury risk of the knee joint in traffic accidents. It focuses on vulnerable road users in car collisions. The situation for knee injuries has been influenced by the changing shapes of vehicles over the last decades. An analysis of real world accidents was carried out by ARU-MUH on the methodology of in-depth-investigation by GIDAS (German-In-Depth-Accident-Study). The data were collected based on the spot documentation in time after an accident event. Accident documentations from 1985 to 2003 are used for this study. In order to determine the influences for the knee injury pattern, two different groups of accident data were compared: years 1985 to 1993, and 1995 to 2003. The vulnerable road users were distinguished as pedestrians, motorcyclists and bicyclists. Only those accidents were selected that involved cars (vans included).

It was found that the highest frequency of knee joint injuries can be established for motorized two-wheelers, i.e. 42% of motorcyclists suffered knee injuries in accidents 1985-1993 compared to 36% in 1995-2003. The lowest frequency can be established for pedestrians, where 22% were injured at the knee in the course of accidents in 1995-2003. The study describes the frequencies of knee injuries in total (soft tissue lesions, ligament tears and fractures) as well as for the different bony and ligamental parts of the knee joint (condyle, patella and tibia) found between 0.5 to 2.6% in the accident sample as a representative value for different kinds of vulnerable road users. The accident severity conditions under which such injuries happened are shown, along with a causation/mechanisms analysis. In case of a serious injury (AIS 2/3) for pedestrians, fractures of tibia head can often be observed (50.8 %), for motorcyclists, tendon ruptures and ruptures of anterior cruciate ligament are very frequent (36.7% / 20.9%). The study shows that there is currently a low overall injury risk for the knee of vulnerable road users in car collisions. Therefore the findings are significant regarding the widespread opinion on risk in literature. The long-term documentation of real world accidents within GIDAS pointed out that the developments in car front shape designing are responsible for the significant reduction of knee injury risk during the last decades.

Keywords

Knees, Biomechanics, Injuries, Fracture, Accident analysis, Bicycles, Pedestrian, Motorcycles.

USUALLY NO SPECIAL EMPHASIS is laid on injuries of the knees in the context of accident outcomes, as they do not have life-threatening consequences. They generally occur as epiphenomenon of slightly or even severely injured road users. On the other hand they cause high consequential costs, as postulated by Dischinger, Miller and Zaloshnja (DISCHINGER 2004; MILLER 1993; ZALOSHNJA 2004). The knee is the largest and one of the most complicated joint of the human body. Eight joint parts cooperate here and allow rotatory movement around its longitudinal axis besides bending and stretching of the lower leg. Additionally, muscle and ligament bundles can be found together with 2 cruciate and 2 collateral ligaments to stabilize the knee. The menisci counterbalance the different bone surfaces between lower and thigh. In the case of an injury of the knee, one or more of these ligamental or bony elements can be damaged and the probability of long-term problems is high due to the complexity (BRAUTIGAN 2000).

During the last decades a significant decrease of casualties and fatalities in road traffic has occurred. Whereas in the year 1971 more than 20 000 dead were registered in Germany alone, 30 years later in the year 2001 only 6000 dead were noted. Owing to the safer passenger compartments, safety belts and airbags that had been introduced, it has been accomplished to continuously lower the risk for injury and the severity of the injuries. Each year in the European Union approximately 17000

vulnerable road users are killed as the result of being strucked by a motor vehicle that are in detail 7000 pedestrians, 3000 bicyclists and 7000 motorcyclists, about 1/3 of the total road traffic deaths. In addition to this, an estimated further five hundred thousand vulnerable road users are injured through vehicle impacts every year, impacted by a car or truck front or side. Early accident investigations identified the most frequently injured body regions of pedestrians to be the leg and head resulting from impacts with the bumper and bonnet. A recent EU Directive[1] has been introduced to address pedestrian injuries, implemented in two phases it utilises sub-system tests to examine the risks of lower leg injury from the car bumper and head injury from the car bonnet. The injury patterns of motorcyclists typically sustained by riders tend to differ from those sustained by other road users. Since the 99% usage of the integral face helmet is protecting the head very well, head injured motorcyclists are registered with approx. 20 % very rare. On the other hand injuries of the lower extremity can be frequently observed particularly the foot and the tibia region can be seen under high injury risk (OTTE 1985). Many of the injury types of motorcyclists, have considerable potential for long-term disability and impairment, especially those to the extremities. Normally drivers of bicycles are grouped with pedestrians and motor-cyclists and many of the casualty reduction estimations for the recent EU pedestrian Safety Directive included estimates for bicyclists calculated on a similar basis to pedestrians. This resulted in a concentration of the protection measures to vital body parts especially the head; measures concerning extremities on the other hand were usually not sufficiently realized. Thus increasingly frequently reports occurred, complaining about injuries to the lower extremities (RICHTER 1999). These injuries are frequently associated with long-term consequences (OTTE 1985), especially where injuries of the feet and the knees are concerned. It is thus not surprising when accident analyses found a significant decrease for injuries of the knees especially where the occupants were concerned, less however for vulnerable road users, pedestrians, bicyclists and motorcyclists.

Most of the existing studies on knee injury situation are based on medical and biomechanical reports of physicians and engineers (ATKINSON 2000; ATKINSON 2003; IAKOVAKIS 2003) or has with special emphasis on the development of dummies and computer simulation, primarily for passengers. Studies for vulnerable road users usually refer to the knees of pedestrians. Yang (YANG 1997) reported in a contribution on the mathematical simulation of knee movements resulting in fractures of the leg and injuries to the knees of pedestrians from his point of view, fractures of the tibia and/or knee injuries such as ruptures of the ligaments and fractures of the condyles were frequently found in experimental studies; he mentions studies by Bunketorp, Aldman, Kramer, Pritz and Cavallero (ALDMAN 1985; BUNKETORP 1983; CAVALLERO 1983; KRAMER 2005; PRITZ 1978). Also accident analyses report knee injuries by Appel, Ashton and Maki (APPEL 1978; ASHTON 1975; MAKI 2003).

A study carried out by *Teresinski* (TERESINSKI 2001) found in a post mortem investigation at the Department of Forensic Medicine in Dublin, knee joint injuries in 214 out of 357 fatal pedestrian victims of traffic accidents (60%). He pointed out that knee injuries are frequently observed in pedestrian victims of traffic accidents and in his description of mechanisms he showed that the cross-section of tibial and femoral epiphyses bone bruises due to compression and avulsion and the bone bruises in the central tibial and femoral condyles were observed only in victims hit in an upright position. There should be a strong correlation between the side of impact on the extremities in medium sized pedestrians (from the front, back, lateral and medial side) caused by passenger cars and the mechanism of knee injuries (hyperextension, anterior dislocation of the proximal tibial epiphysis in relation to the femoral condyles, valgus and varus flexion).

Maki reported about an in-depth analysis by ITARDA, includes 169 vehicle-bicyclist collisions in Japan for the years 1993 to 1997 (MAKI 2003). He postulated that the bonnet leading edge caused femur, tibia and fibula fractures in bicyclists, whereas it caused only femur fractures in pedestrians. In contrast, tibia and fibula fractures in pedestrians are associated with the bumper and front apron contact. It is considered that due to be bent-knee posture of bicyclists, their legs are apt to be impacted by a higher location on the vehicle compared with pedestrians. In the study of Maki only one case of

[1] Pedestrian Protection Directive 2003/102/EC.

ligament damage was found for bicyclists. This type of injury is regarded as one of the criteria in pedestrian leg form tests.

The term "bumper fractures" as a synonym of tibial condyle fractures was introduced by orthopedic surgeons in the 30s (DIETZ 1986). Lower automobile chassis and low front bumpers introduced later resulted in a significantly reduced number of "bumper" tibial condyle fractures and "bumper" fractures were most frequently observed in the regions of the shin bones diaphyses (particularly the bending ones of Messerer's type). However, in modern vehicles the "classic" bumpers were widened and integrated in the front. Teresinski (TERESINSKI 2001) postulated that paradoxically, this "redistribution" of the energy of impact increases the risk of joint injuries and damage to the ligaments results in higher frequency of disability than even multifractures of the diaphyses.

BASIS OF THE STUDY AND METHODOLOGY

In a statistic analysis of traffic accidents documented on-site from the years 1985 to 2003 the Accident Research Unit at the Hanover Medical School checked vulnerable road users for knee injuries. The accidents were recorded at the site of the accident by a scientific team consisting of physicians and engineers and the injuries are documented by an independent documentation including medical reports and x-rays. The documentation contains graphic material and tracings of the site of the accident, a detailed survey of the damages to the vehicles and a reconstruction of the motion sequence, using computer assisted simulation (PC-Crash).

From these data causes of the injuries, their type and extent could be described. The classification of the severity of the injuries was conducted according to the AIS (AMERICAN ASSOCIATION FOR AUTOMOTIVE MEDICINE 1998). After the cohorts were set up for the years 1985-1993 and 1995-2003 all cases with an injury of the knee were filtered out of the overall sample of injured traffic victims. In parallel the technical analysis of the accident mechanisms and loads was conducted. Subsequently, the analyzed characteristics were compiled and evaluated for statistic pertinence using statistic tests.

DATA BASIS

Accident documentations from 1985 to 2003 are used for this study. The documented accidents are traffic accidents with personal damage that were recorded by a team of scientific researchers within GIDAS (German In-Depth Accident Study[2]), and that are stored in a database collected in a statistical sampling and statistical weighting procedure. A total of, 11111 accidents of all traffic participants for the years 1985 to 1994 and 11693 accidents for the years 1995 to 2003 (current situation) are available. From these the injury frequency of the knee for all types of traffic participation (occupants of a cars and trucks, vulnerable road users) including the slight soft tissue injuries were determined in the course of this study. From these a further selection of knee injuries AIS 2+ was checked by an orthopedic trauma resident based on the AIS-classification and the medical evaluation of the injury image and injury pattern of the knee was elaborated.

In order to determine the influence of car shape developments for the injury and the severity outcome of the knee injury pattern of vulnerable road users and finding the characteristics and mechanisms of knee joint injuries on one hand, only two different groups of accident data were compared, in which a car hits a vulnerable road user: the years 1985 to 1993 (n=2739 persons), and 1995 to 2003 (n=2749 persons); for describing the injury risk of knee joints the position to all traffic participants is pointed out where necessary on the other hand, therefore the accidents with injuries to the knee were compared to all accidents of traffic participants. The vulnerable road users were differentiated as pedestrians (n=1794), motorcyclists (n=742) and bicyclists (n=2728). Only those accidents were selected that involved cars (vans included). The persons with AIS 2+ knee injuries were 87 pedestrians, 40 bicyclists and 48 motorcyclists.

[2] sponsored by BASt (Federal Highway Research Institute) in cooperation with FAT (Automotive Industry Research Association)

ANATOMICAL DEFINITION OF KNEE JOINT INJURIES

Injuries of the knee cover the areas from the distal femur epiphysis with condyles up to the tibial plateau with epiphysis, as well as all connecting structures, ligaments including bone insertions, menisci and the patella and the soft tissue surrounding these structures.

In the study the knee was subdivided according to its anatomic structure the femur condylus, tibial plateau, corpus adiposum in frapatellare, patella and the ligamentary connections of cruciate and collateral ligaments (Figure 1).

The AIS-classification ranks contusions and smaller soft tissue wounds as AIS 1, soft tissue defects of greater extension (distortion) with injuries of bursa, ligaments or menisci, patella fractures, closed minimally dislocated fractures of the tibia, knee dislocations and an opened joint are ranked as AIS 2 and fractures of the distal femur, open dislocated or multi-fragmented proximal tibia fractures, complete posterior cruciate ligament ruptures and open ligament ruptures are classified as AIS 3, the highest degree of injury severity on the knee.

In the course of this study the knee injuries were evaluated concerning the occurring mechanics that were operative during the impact and subsequently applied to the knee unit. For this purpose, the position of the pedestrian or the cyclists that was derivable from the reconstruction of the accident was taken into account and the resulting kinematics were determined from the damage to the vehicle and the evaluated throwing motion and differentiated according to the occurring load characteristics as direct impact, bending, rotation and combinations of these.

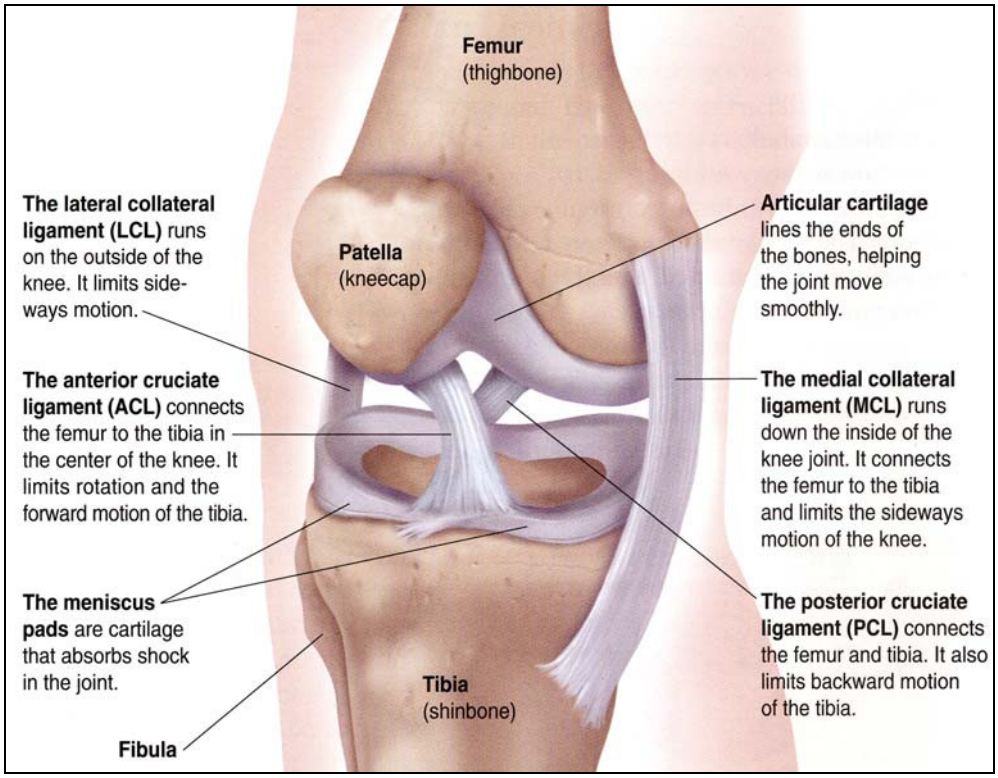


Figure 1 - location of injuries of knee

Additionally, the classification of the different tibia fractures known from scientific, clinical diagnostics according to Schatzker was used (STEVENS 2001). It provides degrees of severity from 1 to 6. Schatzker postulated that usually high-energy injuries caused by varus or valgus stress in combination with axial loading are more or less responsible for tibia fractures at the plateau region. It is important to note the integrity of soft tissue envelope and exclude associated neurovascular injuries in higher-grade fractures. He distinguished between grades

- I - split fracture of the lateral tibial plateau without articular depression
- II - split depressed fracture of the lateral tibial plateau
- III - isolated depression of the lateral plateau
- IV - fracture of the medial plateau

V - bicondylar plateau fracture with varying degrees of articular depression and displacement of the condyles
VI - bicondylar tibial plateau fracture with diaphyseal metaphyseal dissociation

FREQUENCY OF KNEE INJURIES IN TRAFFIC ACCIDENTS

Injuries in the knee area are luckily rather infrequent as results of traffic accidents. If simple soft tissue injuries of the skin are included, today about 17.2% of all persons injured in a traffic accident suffer an injury in the knee area (Table 1). The statistically representative material of the Accident Research Unit Hanover shows a significant reduction compared to the accident occurrence of 20 years ago. Where 23.5% of such injuries recorded in those years (1985 to 1994), about 10 years ago (1995 to 2003) only 17.2% of the injuries included the knee. Table 1 reveals that for all traffic participants a significant reduction of the injury frequency has occurred ($p < 0.0001$ chi-square-test). Knee injuries are generally more frequent in vulnerable road users, whereas occupants of cars suffer least at currently 10%. Especially motorcyclists are strongly at risk of such an injury at 36.1%. Bicyclists as well as pedestrians suffer such injuries at 25.4% or 21.8% of all cases.

	total	kind of traffic participation				
		car occupant	truck occupant	motor-cyclist	bi-cyclist	pedes-trian
year of accident 1985-1993						
total (n)	11111	5891	401	1052	2304	1463
head	47.7%	48.1%	51.3%	23.2%	52.3%	55.8%
neck	19.9%	33.1%	22.2%	7.8%	4.9%	4.1%
thorax	29.8%	37.6%	24.6%	22.5%	20.9%	22.0%
upper extr.	37.1%	28.0%	36.9%	49.2%	47.6%	44.4%
abdomen	8.2%	9.0%	8.1%	7.7%	6.3%	8.8%
pelvis	10.7%	7.8%	7.4%	16.0%	12.2%	16.3%
thigh	9.2%	4.8%	7.8%	16.9%	12.1%	15.5%
knee	**23.5%**	**14.4%**	**22.0%**	**42.2%**	**31.5%**	**30.9%**
lower leg	16.0%	9.0%	13.0%	29.0%	20.9%	25.7%
foot	13.2%	7.1%	7.9%	29.6%	17.2%	18.2%
year of accident 1995-2003						
total (n)	11693	6824	507	1227	2018	1117
head	36.6%	35.1%	45.0%	17.0%	42.1%	52.8%
neck	30.2%	46.7%	38.1%	7.5%	5.6%	4.9%
thorax	27.6%	31.2%	32.9%	26.3%	20.5%	19.9%
upper extr.	31.3%	22.4%	42.8%	45.0%	44.3%	37.4%
abdomen	6.8%	6.7%	15.5%	6.9%	5.1%	7.4%
pelvis	8.2%	5.0%	12.1%	14.6%	10.7%	13.4%
thigh	4.7%	2.5%	5.1%	9.4%	6.6%	8.7%
knee	**17.2%**	**10.0%**	**16.6%**	**36.1%**	**25.4%**	**21.8%**
lower leg	9.6%	5.0%	10.6%	17.6%	14.6%	17.6%
foot	7.7%	3.3%	4.9%	17.6%	12.7%	14.1%

Table 1 - frequencies of injured body regions of casualties of traffic accidents

Thus it was shown that „vulnerable road users“ suffer more frequently injuries of the knee than occupants of cars or trucks. Generally a significant decrease for all persons participating in traffic can be seen in the course of the last decades, but this decrease is not as drastic as for the passengers. The aim of this study is to closely investigate the injury situation of the knees of the group of vulnerable road users and to identify the loads and mechanisms occurring in the course of the collision, in order to suggest counteracting measures for this exponent group.

If the investigation is exclusively limited to bony and ligamental injuries of the knee area, such injuries occur in less than 3% (Figure 2). They occur currently (1995 to 2003) at 1.2% of the pedestrians (used to be 2.6%), at 0.5% of the bicyclists (used to be 0.8%) and 1.6% of the motorized two-wheelers (used to be 1.9%).

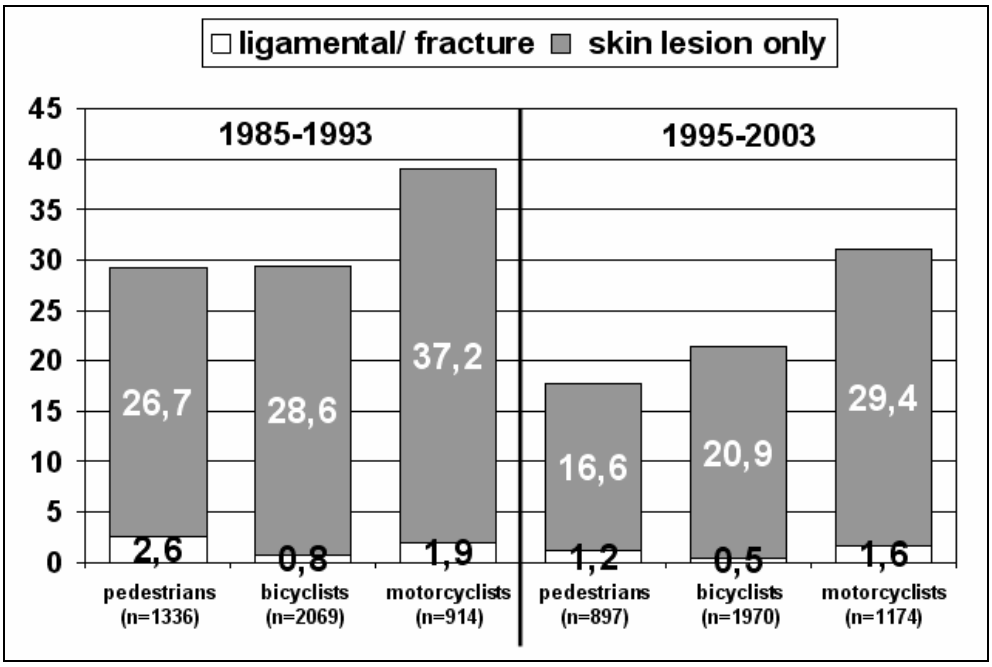


Figure 2 - frequencies of knee injuries for different traffic participations (100% all persons each group)

ACCIDENT FRAMEWORK AND CHARACTERISTICS

The collision events of vulnerable road us are determined by the impact velocity of the car and for two-wheel drivers additionally by the collision angle and the movement of the cycle.

Persons suffering from injuries have frequently been injured at other parts of the body as well (Figure 3).

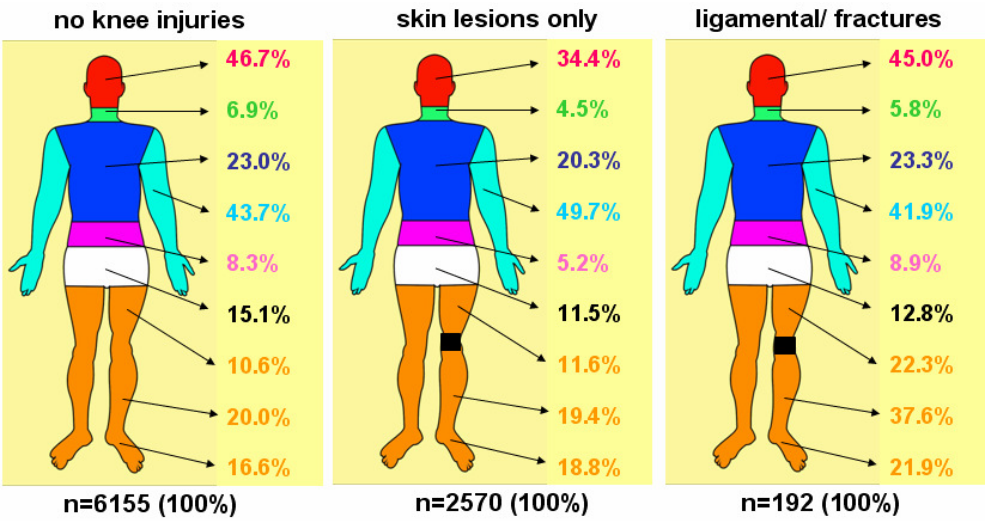
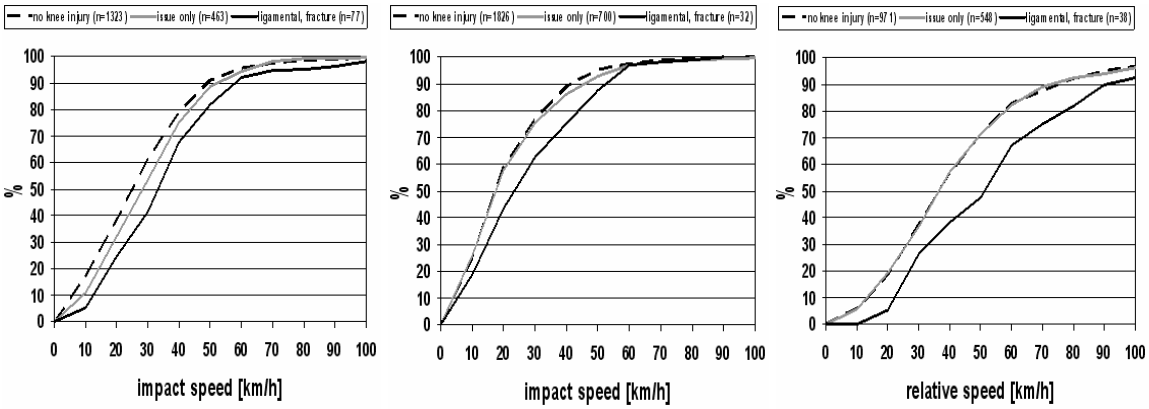


Figure 3 - frequencies of injured body regions of vulnerable road users

Thus 45% of the persons with osseous and/or ligamental injuries of the knee suffered also from injuries to the head (47% without injury of the knee), 23% to the thorax (23% without injury of the knee too), 13% to the pelvis (15% without injury of the knee). It is remarkable that persons with bony or ligamental knee injuries suffered from injuries on the tibia/fibula region in a higher frequency of 38% as well. Closely related are higher impact velocities, which were observed for knee injuries (Figure 4).



pedestrians bicyclists motorcyclists

Figure 4 - cumulative frequencies of impact speeds of car compared for victims with and without knee injuries

70% of all measured impact velocities rated between 20 and 60 km/h of the car, for pedestrians as well as bicyclists, whereas for patients without knee injury they rated 10 to 50 km/h. For motorcyclists 70% of the determined relative velocities were found to be between 20 and 75 km/h, these occurred for motorcyclists with knee injuries at 30 to 90 km/h. Thus the impact speed is a dominant predictor for knee injury risk and is following in more injury severity of the whole human body. The resulting severity of the injuries of patients with knee injuries was significantly higher (Figure 5). Only 41.6% of the persons with knee injuries were assigned with a rate for minor injury MAIS 1 and 23.1% had a MAIS 3+ (without knee injuries 6.6 %).

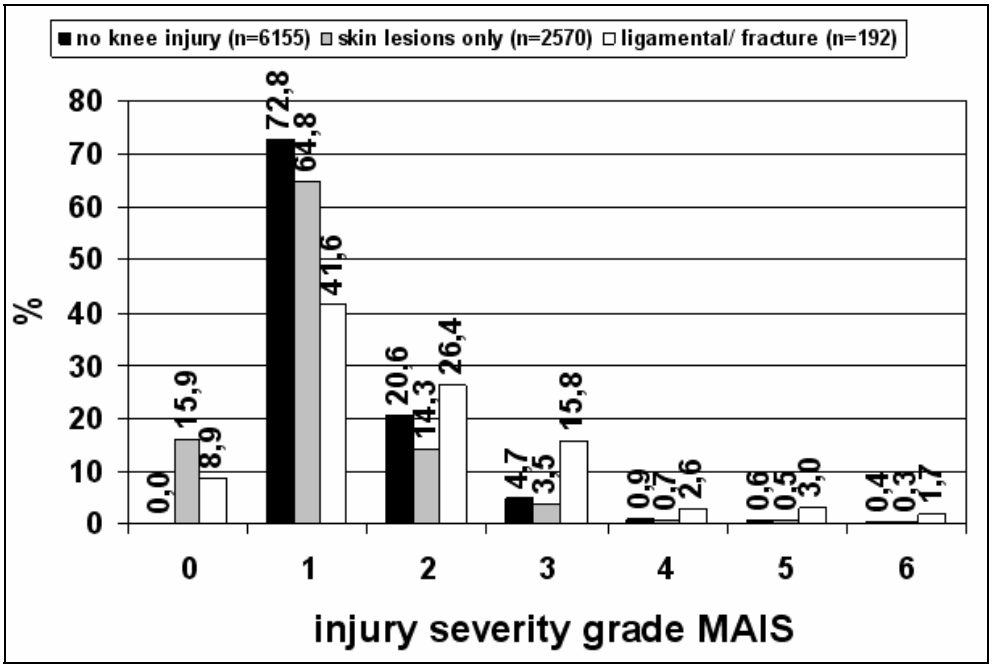


Figure 5 - maximum injury severity grade MAIS (without knee injuries) of vulnerable road users compared for persons with and without knee injuries

TYPE OF KNEE INJURIES

In case of a severe knee injury motorcyclists suffer more frequently than other road users ruptured tendons of the bursa (36.7%) and the anterior crucial ligaments (20.9%), whereas pedestrians frequently suffer from tibia plateau fractures (50.8%) and medial collateral ligamental lesions (20.7%). Injured bicyclists frequently show fractures of the patella (17%) and of the tibial plateau (27.2%). Injuries of the condylus, of the meniscus and the lateral collateral ligaments were detected relatively rare, especially for bicyclists (Figure 6).

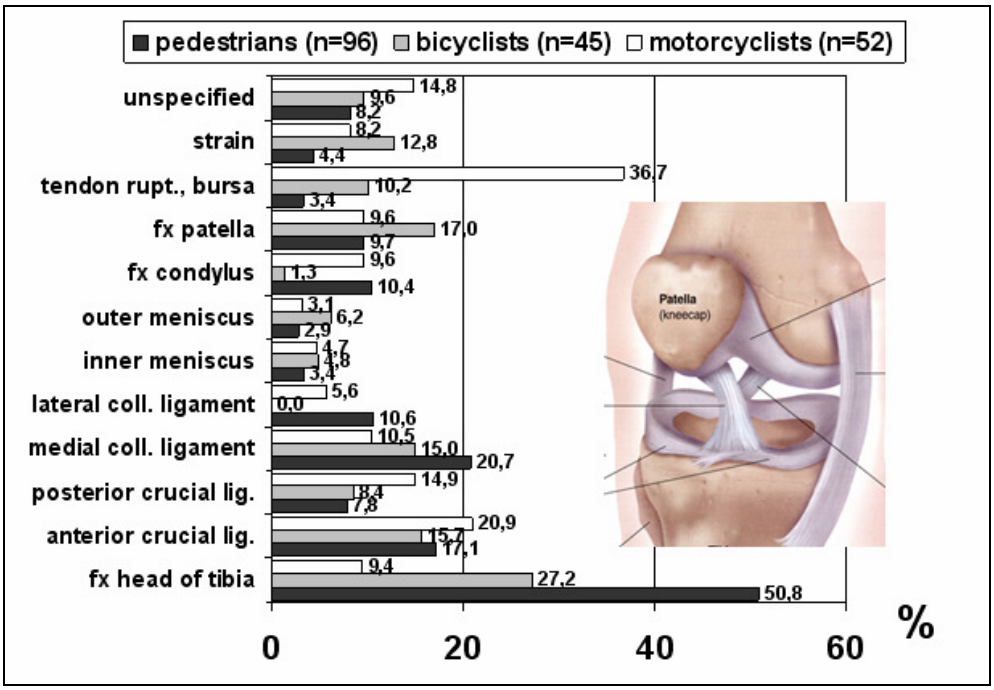


Figure 6 - anatomical related kind of injuries of knee (100% all persons each group of participant)

COLLISION MECHANICS OF THE KNEE IMPACT TRAUMA

Formally, the knee is a rotatory and a hinge joint, as rotationary movement of the knee is possible besides the bending and stretching movement. The joint cohesion and the movements of the joint elements are mainly supported by muscle forces and ligaments.

Based on the injuries patterns of all injuries that occurred at the knee and the information of the impact kinematics, the mechanics of the injuries was evaluated by an experienced team of physicians and engineers for individual cases (Figure 7 and Table 2).

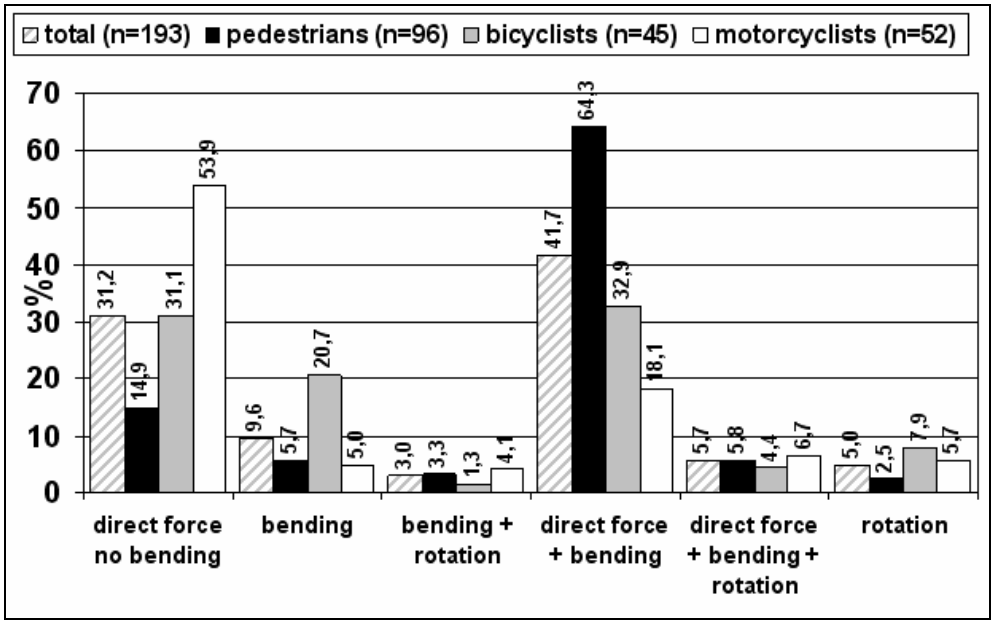


Figure 7 - mechanisms of knee injuries

A direct impact force (the bumper hits the knee direct without inducing rotation or a bending motion) was responsible in 31.2%, in 9.6% bending and in 5% rotation can be seen as mechanisms. In 41.7% a combination of direct force plus bending could be established in many cases. A difference in

the collisions of the individual types of traffic participants was noted. Pedestrians frequently suffered from at 64.3 % direct force + bending, whereas motorcyclists at 53.9% frequently suffered from direct force without bending. Knee injuries based on isolated rotation was in contrast detected relatively infrequently. In most of the cases rotation occurred together with bending.

Table 2 shows that ruptures of the patellar tendon result from direct impact while all other injuries to the knee region include bending and/or rotational motions.

mechanism / anatomical region	n	direct force no bending	bending	bending + rotation	direct force + bending	direct force + bending + rotation	rotation
unspecified	19	30.1	16.7	-	23.8	17.5	12.0
sprain	11	23.9	15.2	4.6	5.2	-	51.1
patellar tendon rupt.	28	87.0	-	-	6.0	7.0	-
fx patella	23	43.2	-	-	39.1	17.6	-
fx condylus	14	53.7	-	-	43.6	2.7	-
outer meniscus	8	16.0	10.7	-	73.3	-	-
inner meniscus	8	14.8	9.9	9.1	61.2	5.0	-
lateral coll. ligament	13	32.9	6.7	-	46.7	13.7	-
medial coll. ligament	32	10.9	17.2	13.8	53.6	4.6	-
posterior crucial ligam.	21	14.2	22.5	-	55.0	8.3	-
anterior crucial ligament	33	17.2	19.1	5.7	53.5	4.5	-
fx head of tibia	75	23.7	5.8	2.6	63.3	4.6	-

Table 2 - mechanisms of different knee injuries related to different kind of anatomical region of knee (total n = 285 injuries of 193 victims)

SPECIAL MECHANICS ON PEDESTRIAN-CAR IMPACTS

A high risk for knee injuries arises obviously in the case of an impact of a car to the right side of a body (Figure 8) because this situation lead in high loads to the knee elements. Where 32.6% of all pedestrians with no knee injuries had an impact from the right, 47% of all pedestrians who suffered from injuries to ligaments and bones of the knee were hit from the right. Such an over representation was not apparent for the other sides of impact.

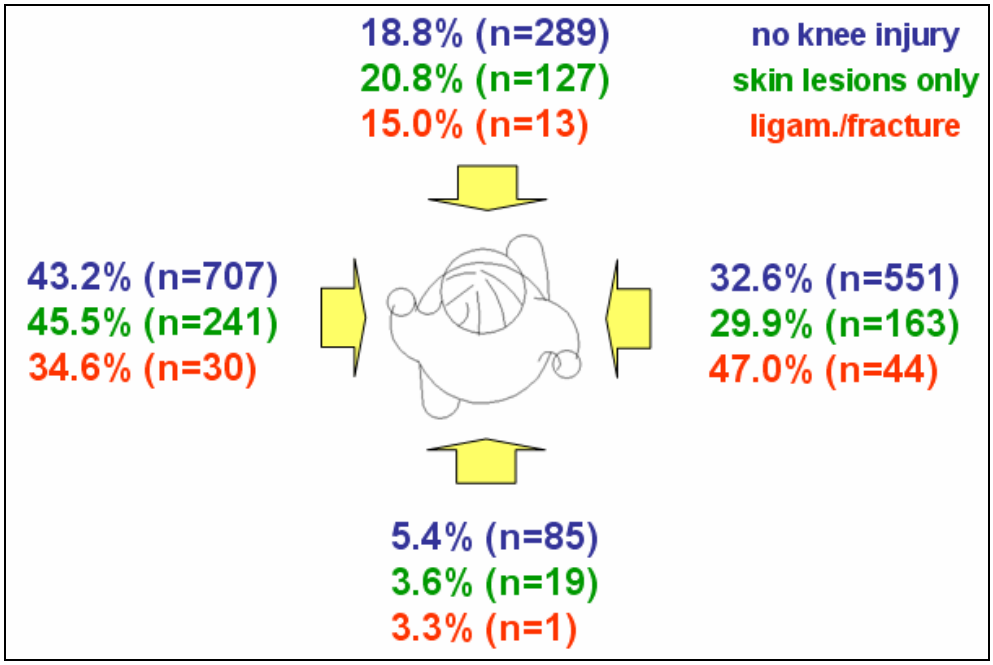


Figure 8 - impact directions of pedestrians comparing persons with and without knee injuries

Figure 9 shows the individual injured anatomical parts of the knee joint in relation to the velocity of the impact. It is noticeable that simple distortions, injuries of the outer meniscus and the lateral collateral ligaments occurred at rather lower speeds, whereas injuries of the inner meniscus, and the posterior crucial ligaments occurred at higher impact velocities. The tibia plateau fractures that occur especially frequently on pedestrians occurred at all velocities and should thus be molded by the special kinematics, where a bending is induced on the knee joint.

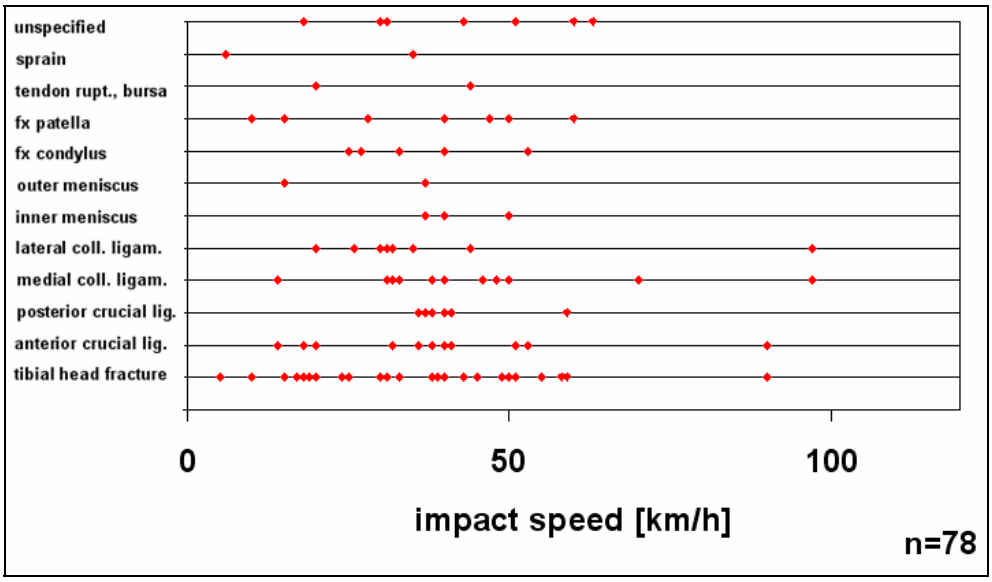
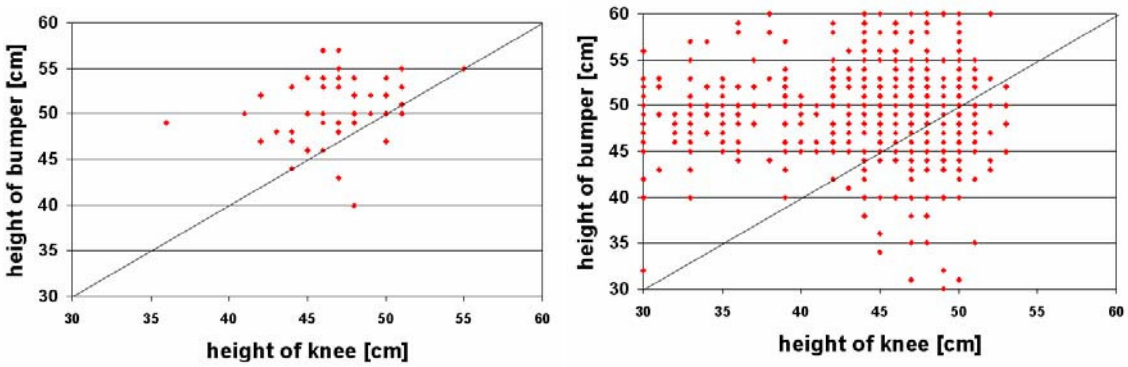


Figure 9 - anatomical kind of injured part of knee joint of pedestrians related to impact speed of car

It could be analyzed (Figure 10) that much more knee injuries occurred if the height of the knee joint above road surface was larger than the height of the bumper transfer the impact load (with fracture/ligamental lesion 7 of 55 (13.4%) - without 169 of 727 (23.2%)) The nonparametrical Mann-Whitney statistical test is pointed out an asymptotical significance value of p=0.032. Height of bumper is the measurement of the upper edge of bumper above road level. The comparison of mean values for bumper heights for pedestrians with knee injuries (1.07) and those without knee injuries (1.19) is highly significant (Levonne test $p < 0.0001$).



with fx / ligamental injury of knee (n=55) without knee injuries (n=727)

Figure 10 - bumper height and knee height for pedestrian accidents comparing persons with and without knee injuries

It was investigated if the struck sided knee was injured or the opposite one (Figure 11). For this analysis all laterally collided pedestrian and bicyclists with knee injuries were put together and found that strains (86.2%), outer meniscus lesions (100%), fractures of condylus (73.7%) and of tibia head (74.8%) mostly linked with the struck side. In contrast, fractures of patella (34.4%) and inner meniscus lesions (48.6%) and tendon ruptures (40.5%) were often injured on non-struck-side of the legs. It can be seen in the diagram that the highest frequent injury location for the non struck sided

knee can be registered for medial collateral ligament lesions (31%) and for the struck side fractures of head of tibia can be seen in 40.4%.

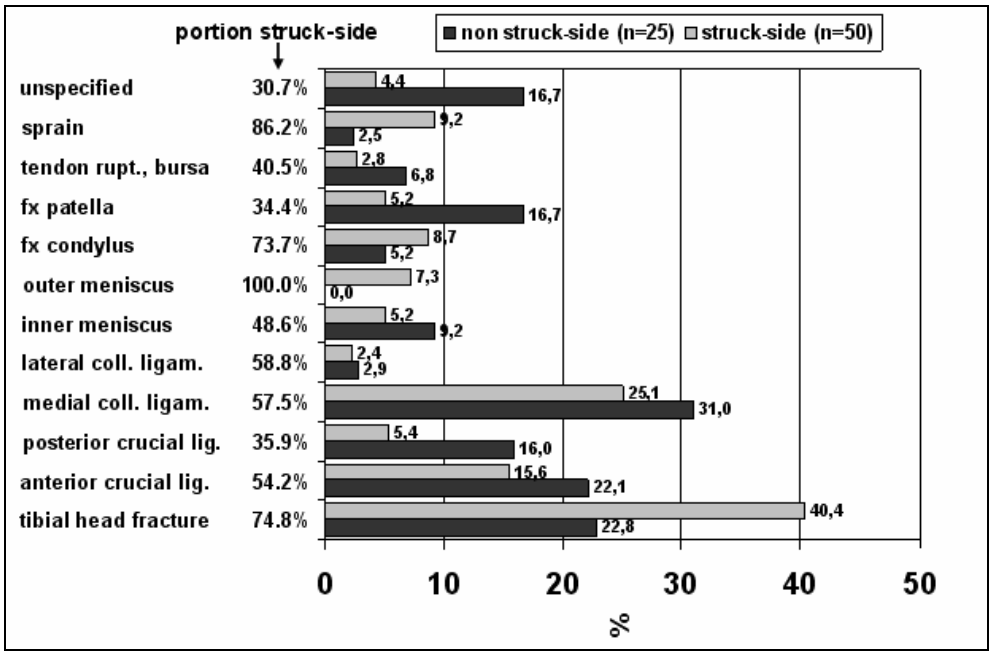


Figure 11 - injured anatomical part of knee joint of pedestrian and bicyclists for struck-side and non-struck-side of impact

The influence of the car front shape was investigated by a comparison of 3 different types of shape (Figure 12), selected out of existing geometrical sections in longitudinal axis. Type A is classifying the old 70ies shape with exponent front leading edge and protruding bumper, type B the more smoother one of the 90ies and the new current generation of soft rounded shape type C.

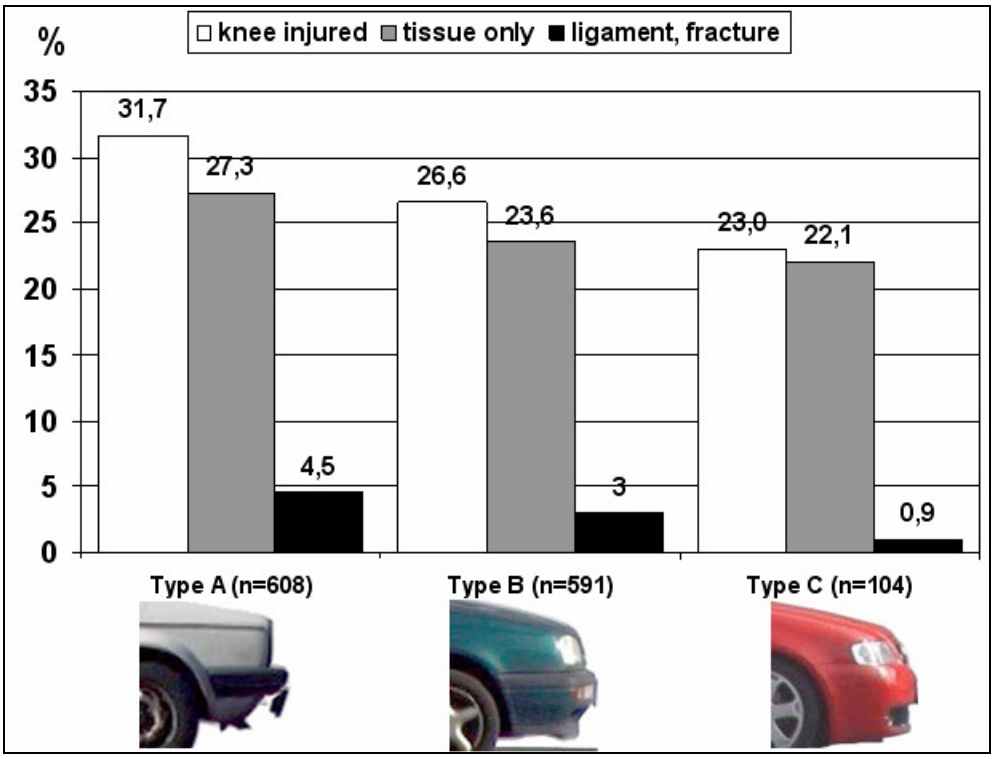


Figure 12 - types of front shape in influence to knee injuries of pedestrians

While 31.7% of the pedestrians hit by a car type A suffered knee injuries and 4.5% received ligamental injuries or fractures to the knee, only 23.0% suffered knee injuries and remarkable 0.9% could be registered with ligamental injuries of fractures hit by car type C. The new car front shape design seems to be responsible for the high due of decrease of knee injury risk, this is the result of the statistical liner bilinear association test p = 0.0015.

SPECIAL MECHANICS ON BICYCLE-CAR IMPACTS

61.4% of all collisions between cars and bicycles resulting in an osseous/ligamentary knee injury occur at near right angles, where the front end of the vehicle hits the side of the bicycle (Figure 13). In contrast, this type collision configuration occurs only at 38.3% of all bicyclist accidents without knee injury and in 37.2% of bicyclists with tissue lesions only. The figure shows that there is a very definite risk for all collisions where the front end of a vehicle hits the bicyclist (3.5% in type 3 and 1.8% in type 4 only).

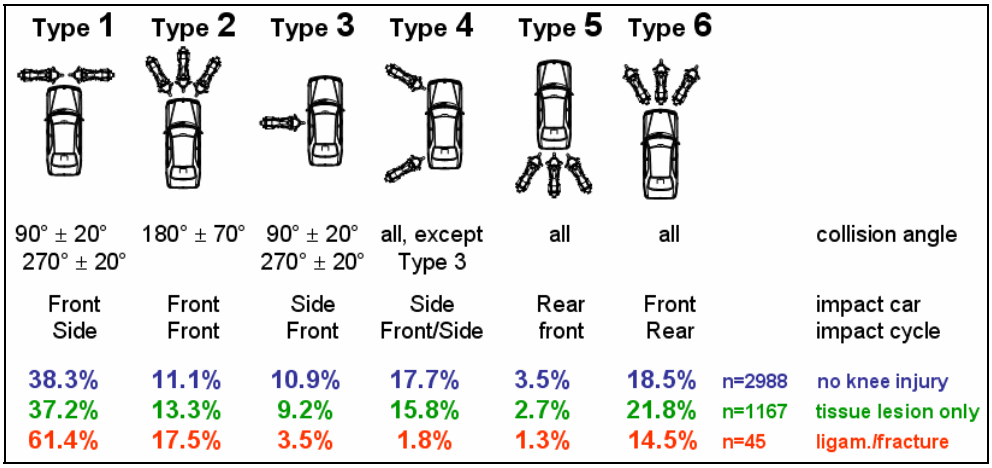


Figure 13 - collision configurations of bicycle to car impacts comparing for victims with and without knee injuries

Figure 14 displays the individual injured parts of the knee joint in relation to the impact velocity. It is apparent that similar to the position of the pedestrians, simple distortions, injuries of the outer meniscus and the lateral collateral ligaments occur rather at lower speeds. Injuries of the inner meniscus, the posterior crucial ligaments are much rarer. The tibia plateau fractures that frequently happen to pedestrians also occur much less frequently and then at lower velocities; in this instance it can be assumed that the bent knees of the bicyclist and the special impact kinematics between the car front and the laterally impacted cycle a bending of the knee joint is already induced at lower velocities.

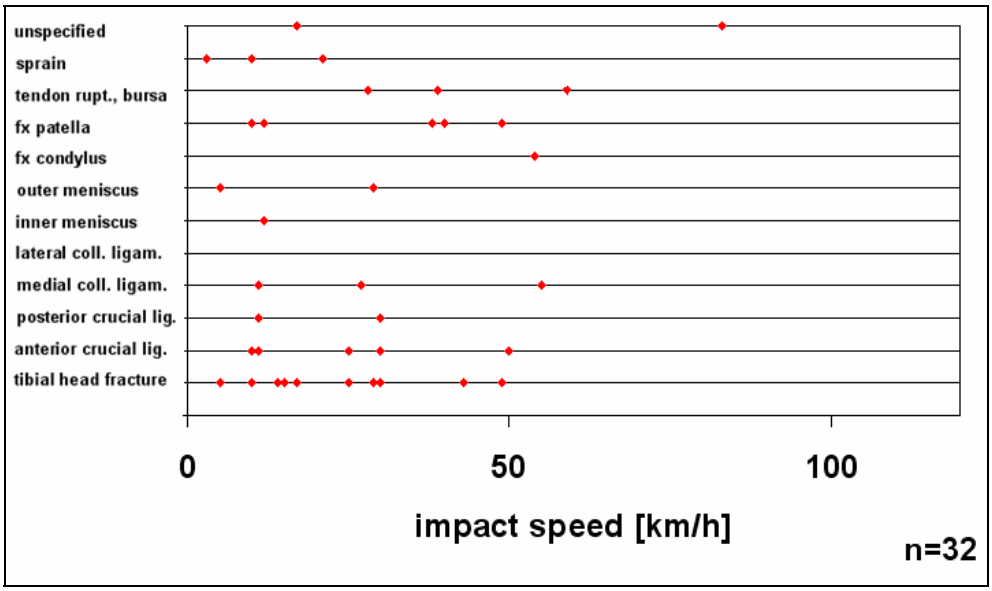


Figure 14 - injured anatomical parts of knee joint of bicyclists and impact speed of car

SPECIAL MECHANICS ON MOTORCYCLE-CAR IMPACTS

For motorcyclists the angled to frontal impact of the motorcycle to the front of the car seems to be especially dangerous where osseous/ligamentary knee injuries (32.5% of all persons with knee injuries in comparison to 17.3% without knee injury) are concerned. In contrast, the exactly perpendicular impact of a car front against the side of the motorcycle does not seem to increase the risk for knee injuries (Figure 15). This type of head on collisions constitutes 10.3% of all collision situations of the motorcycle driver against a car, this type of collision was also present for those 5.8% that suffered only bony of ligamental injuries of the knee.

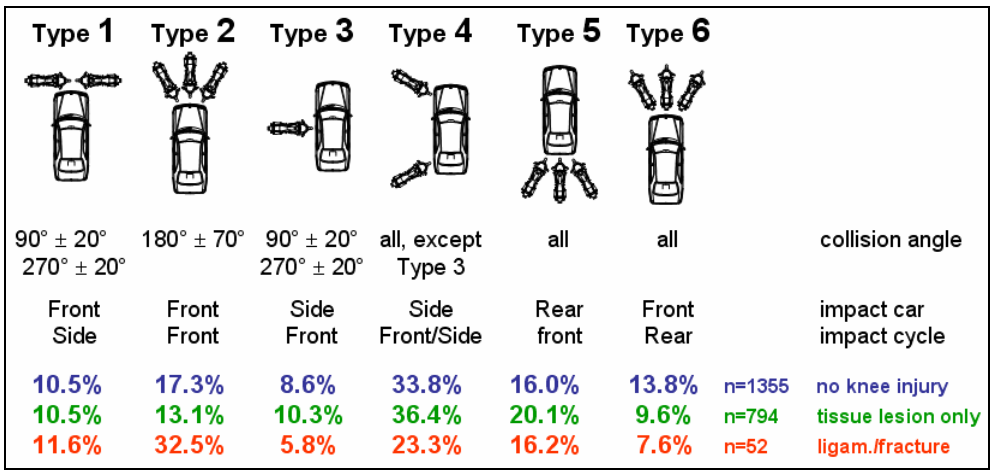


Figure 15 - collision configurations of motorcycle accidents compared for victims with and without knee injuries

Figure 16 displays the individual types of injury to the knee in relation to the relative speed. For motorcycle accidents it could be found in previous studies that the relative speed is a major influence parameter for the resultant injury pattern of the motorcyclist (OTTE 1989). This vector is best considering the different possible speed vectors of the motorcycle on one hand and the collided car on the other hand. It is apparent that for bicyclists and pedestrians the simple distortions and injuries of the outer meniscus and the lateral collateral ligaments occur at rather lower velocities, whereas motorcyclists suffer them at rather higher speeds. Injuries of the medial collateral ligaments and tibia plateau fractures for the latter occur at lower impact speeds, however. Tendon ruptures and bursa injuries seem significantly related to higher relative velocities.

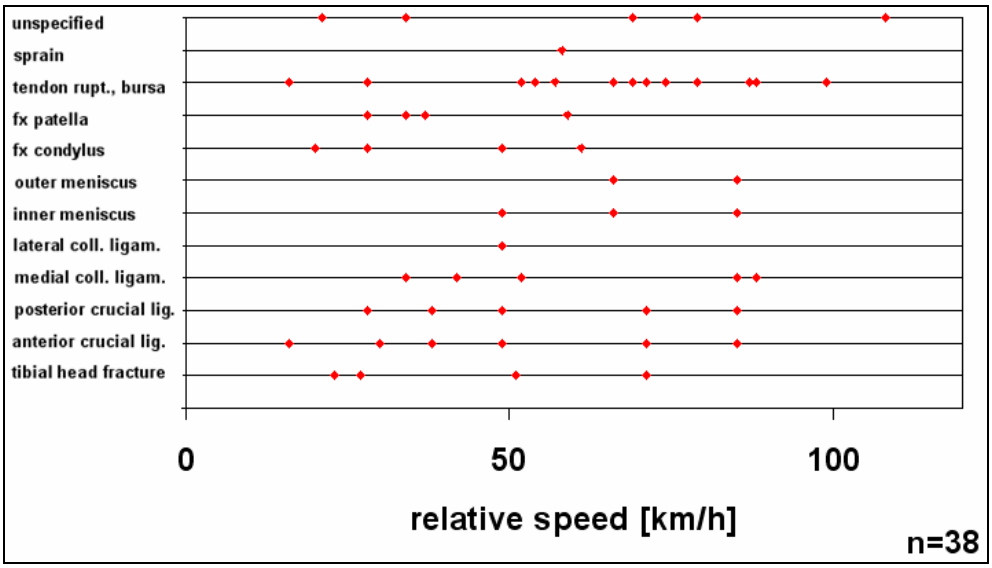


Figure 16 - injured anatomical parts of knee joint of motorcyclists and impact speed of car

It could be seen that patella fractures are mainly the result of a frontal direct impact to the knee (Figure 17) and the ligaments are mainly injured under rotational bending followed on lateral impact conditions. There injuries as strains (24.6%) and lesions of anterior crucial ligaments (37.2%) as well as fractures of tibia plateau (16.2%) could be seen very often.

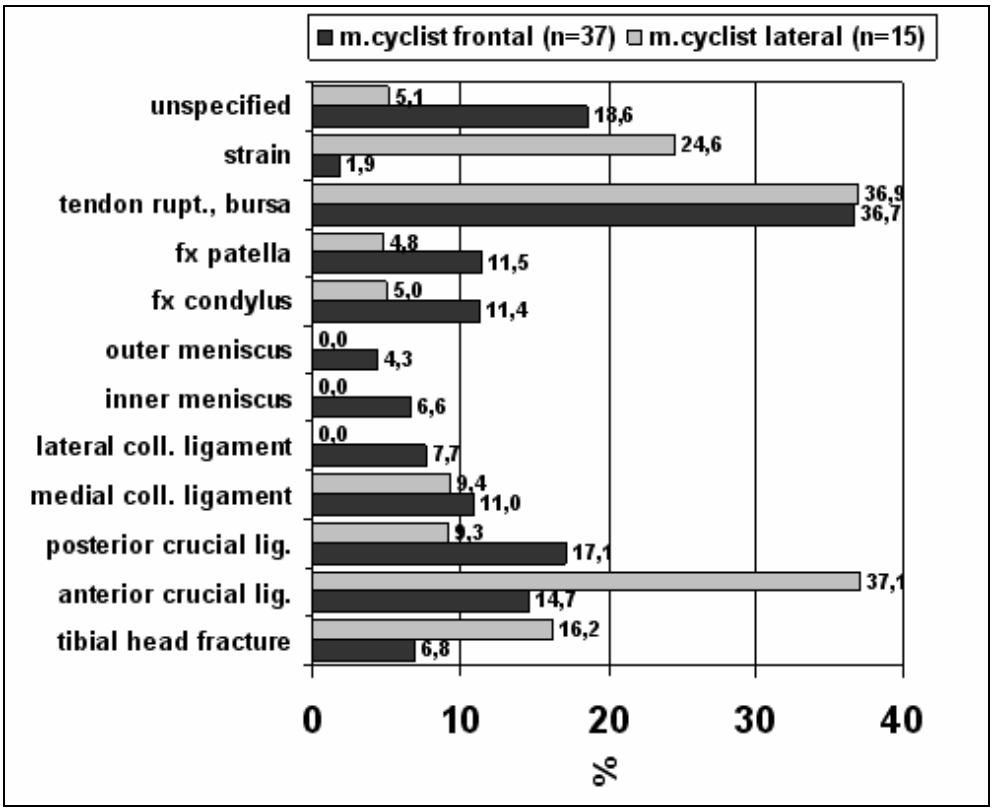


Figure 17 - injured anatomical part of knee joint of motorcyclists and impact direction

MECHANISMS AND INFLUENCE TO KNEE INJURY

It is remarkable that a lateral impact results very often in a tibia plateau fracture. This can be seen especially in car to pedestrian accidents but also in car to bicycle collisions and can be as opposed to many studies, claiming that a valgus stress and an increase in force to the medial collateral ligament, which in turn then tears, occurs. The analyzed mechanism for the tibia plateau fracture is related mainly to a lateral impact with bending of the ligaments. In the course of the accident, the medial

collateral ligament seems to last and the increase in force seems to lead to pressure on the lateral compartment, i.e. the femur condylus is pressed on the tibial plateau while the medial collateral ligament resists, resulting in a tibia plateau fracture. Therefore 16.2% of the lateral collided cyclists with knee injuries suffered a tibia plateau fracture and 40.4% of the pedestrians suffered this kind of injury on the struck sided leg. This can be confirmed by the resulted severity of the tibia plateau fracture according to Schatzker 1 to 3 (Figure 18) that represents two third of all kind of tibia plateau fractures. The diagram is shown that in contrast to pedestrian and motorcyclists especially tibia plateau fractures type Schatzker 2 can be seen with high frequency of 10.8% for bicyclists.

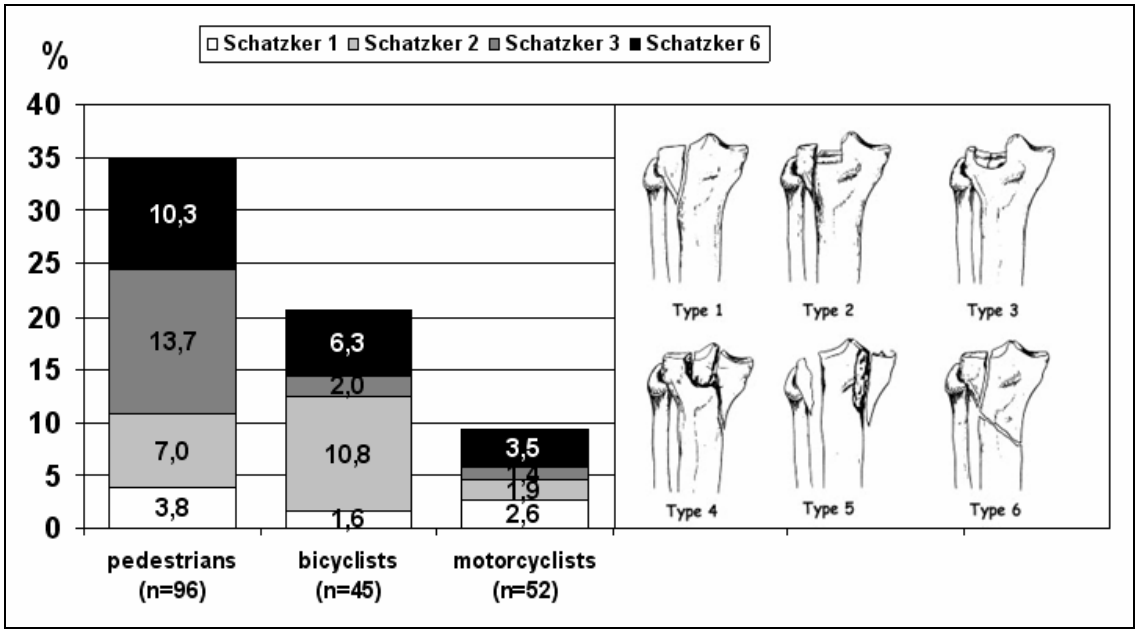


Figure 18 - portion of fractures of head of tibia as classification by Schatzker (STEVENS)

CONCLUSION

This study on knee injury mechanisms based on in-depth-investigations at accident sites in Hanover demonstrated that the high risk for osseous and/or ligamentary injuries of the knee that has been described in publications could no longer be postulated. In contrast it can be stated that only 1.2% of the pedestrians involved in road traffic accidents, 0.5% of the bicyclists and 1.6% of motorized two-wheeler drivers were injured at the knee in the course of a collision with a car. This incidence can be called a low risk. It was also found and statistically estimated ($p < 0.0001$ chi-square-test) that the risk for knee injuries was significantly lower than 10 years ago. A reduction of 27% can be postulated.

Even though the risk of the bicyclist of suffering osseous and ligamentary injuries is twice as low as that of pedestrians, it is still significant at 0.5%. This is in conformity to Maki, postulated in an analysis of investigations at the site of accidents, in Japan, that due to the higher position of the knee for bicyclists as compared to pedestrians the bending moment imposed on the knee area is lower and therefore he could found only one case of ligament damage for a bicyclist. The presented study here showed frequent damage of the ligament structures for bicyclists, whereas pedestrians suffered more frequently from tibia plateau fractures, a special feature of the study was the emergence of tibia plateau fractures with intact ligaments. A special injury mechanism was also found for motorcyclists. In those cases the most frequent injuries were ruptured tendons und injuries of the bursa, an injury pattern that emphasizes the high impact energy, in principle independently of the direction, applying to mostly frontal, but also as lateral impact situations. Motorcyclists are especially injury-prone if the impact occurred frontally in head-on collisions (32% of all motorcyclists with knee injuries), even though this collision configuration occurs only at 17% of all accidents involving a motorcycle.

Knee injuries are not necessarily but in general significantly related to a high impact velocity of the car, they also have been observed for speeds lower than 10 km/h with 10% on one hand, but 60%

occurred at speeds above 30 km/h for pedestrians and above 25 km/h already for accidents involving bicycles, for motorcycle accidents 60% of the relative speeds exceeded 30 km/h.

The height of the bumper seems to have some sort of influence of the development of osseous and/or ligamentary knee injuries. If the bumper induces energy in the area of the knee or above it, knee injuries are extremely significant (Levenne mean value comparison test $p < 0.0001$). This allows the assumption that an optimized height design of the bumper and an optimization of the front end of the car can lead to a reduced risk of injury where a knee impact trauma is concerned.

It could be established from a statistical analysis with significant of $p = 0.0015$ that the smoother front shapes of today cars of the 2000 vehicle generation leads to that low frequency of knee injuries. Comparing to the old car front shapes with extremely mounted bumpers and nearly rectangular front leading edges there can be established a 79% risk reduction for ligamental injuries and fractures on the knee.

The study showed that the motorcyclists are under risk for knee injury if a frontal direct impact to the knee occurs and based on the resulting relative motion of the human body on the motorbike frontally a load is transmitted to the patella following in patella fractures. Based on the following movement of the human off the bike a bending rotation mechanic is possible transmitting stress load to the ligaments on one hand. It is also possible that the tibia is forced posterior relative to the femur. The posterior cruciate ligament is usually tight when the knee is in 90 degree flexion and is therefore at high risk for disruption. This mechanic is known as “dashboard injury” described by Sanders (SANDERS 2000). In contrast to motorcyclists the knees of bicyclists are hit mostly from the side if the car front collides against the lateral part of the cycle. From this a laterally bending moment is induced to the knee.

The study has shown that the mechanisms of knee joint injuries are different for the different vulnerable road user types. Therefore it will be difficult to cover these different mechanisms in one type of dummy or by using pedestrian models only. The conclusions found in the course of this study can be used to improve the current computer simulation of motions and load behavior. They can also supplement the current component tests for the protection of pedestrians concerning kinematics resulting in knee injuries and finally they can also be used to include the requirements for the bicycle impact into such test regulations. The study also reveals how important scientifically oriented in-depth investigations are und that the depth of information also supplies details of comprehensive injury documentation. The investigations conducted under the name GIDAS (German In-Depth Accident Study) in Hannover und Dresden offer such feasibilities.

References

1. Aldman B., Kajzer, J., and Bunketorp, O.: An Experimental Study of a Modified Compliant Bumper, 10th International Technical Conference ESV, (1985), 1035-1040
2. American Association for Automotive Medicine: Abbreviated Injury Scale-Revision 98, Am Ass f Autom Med, Morton Grove, (1998),
3. Appel H., Kuehnel, A., Stuertz, G., and Gloeckner, H.: Pedestrian Safety Vehicle - Design Elements - Results of In-Depth Accident Analyses and Simulation, 22nd AAAM Conference, (1978), 132-153
4. Ashton S. J.: The Cause and Nature of Head Injuries Sustained by Pedestrians, International Research Committee on the Biokinetics of Impacts, 2nd International Conference, (1975), 101-113
5. Atkinson T. and Atkinson, P.: Lower extremity injuries in motor vehicle collisions: a survey of NASS 1997-1999, International Journal of Vehicle Design, 32, (2003), 173-183
6. Atkinson T. and Atkinson, P.: Knee injuries in motor vehicle collisions: a study of the National Accident Sampling System database for the years 1979-1995, Accid Anal Prev, 32, (2000), 779-786
7. Brautigan B. and Johnson, D. L.: The epidemiology of knee dislocations, Clin Sports Med, 19, (2000), 387-397

8. Bunketorp O., Aldman, B., and Eppinger, R.: Experimental Study of a Compliant Bumper System, Ircobi-Stapp-Conference, (1983), 287-297
9. Cavallero C., Cesari, D., and Ramet, M.: Improvement of Pedestrians Safety, Influence of Shape of Passenger Car Front, SAE, 830624, (1983), 225-237
10. Dietz, G. W., Wilcox, D. M., and Montgomery, J. B.: Segond tibial condyle fracture, lateral capsular ligament avulsion, 159, (1986), 467-469
11. Dischinger P. C., Read, K. M., Kufera, J. A., Kerns, T. J., Burch, C. A., Jawed, N., Ho, S. M., and Burgess, A. R.: Consequences and costs of lower extremity injuries, Annu.Proc.Assoc.Adv Automot.Med, 48, (2004), 339-353
12. Iakovakis I., Dessypris, N., Dalamaga, M., and Petridou, E.: A cluster analysis of road traffic-related childhood knee injuries, Child Care Health and Development, 29, (2003), 297-301
13. Kramer M., Burow, K., and Heger, A.: Fracture Mechanism of Lower Legs Under Impact Load, 17th Stapp Car Crash Conference, (2005), 81-100
14. Maki T., Kajzer, J., Mizuno, K., and Sekine, Y.: Comparative analysis of vehicle-bicyclist and vehicle-pedestrian accidents in Japan, Accid Anal Prev, 35, (2003), 927-940
15. Miller T. R., Pindus, N. M., and Douglass, J. B.: Medically Related Motor-Vehicle Injury Costs by Body Region and Severity, J Trauma, 34, (1993), 270-275
16. Otte D. and Appel, H.: Injury Mechanism and Crash Kinematic of Cyclists in Accident - an Analysis of real Accidents, Stapp Car Crash Conference, SAE 892425, (1989), 1-20
17. Otte D., Kalbe, P., and Appel.H.: Difference of Injury Patterns and Accident Kinematic of Motorised and Non-motorised Two-Wheelers, Am Ass f Autom Med, Proc. 29th, (1985), 335-352
18. Pritz H. B.: Comparison of the Dynamic Responses of Anthropomorphic Test Devices and Human Anatomic Specimens in Experimental Pedestrian Impacts, 22nd Stapp Car Crash Conference, (1978), 341-357
19. Richter M., Thermann, H., Rheinbaben, H., Schratt, E., Otte, D., Zwipp, H., and Tscherne, H.: Frakturen der Fußregion bei PKW-Insassen, Unfallchirurg, 102, (1999), 429-433
20. Sanders T. G., Medynski, M. A., Feller, J. H., and Lawhorn, K. W.: Bone Contusion Patterns of the Knee at MR-Imaging: Footpoint of the Mechanism of Injury, Scientifc Exhibit RG, 20, (2000), 135-151
21. Stevens D. G., Beharry, R., McKnee, M. D., Waddell, J. P., and Schemitsch, E. H.: The long-term functional outcome of operatively treated tibial plateau fractures, J Orthop Trauma, 15 (5), (2001), 312-320
22. Teresinski G. and Madro, R.: Knee joint injuries as a reconstructive factors in car-to-pedestrian accidents, Forensic Science International, 124, (2001), 74-82
23. Yang J. K.: Mathematical simulation of knee responses associated with leg fracture in car-pedestrian accidents, IjCrash, 2 No 3, (1997), 259-271
24. Zaloshnja E., Miller, T., Romano, E., and Spicer, R.: Crash costs by body part injured, fracture involvement, and threat-to-life severity, United States, 2000, Accid Anal Prev, 36, (2004), 415-427