A COMPARISON OF MECHANISMS OF ANKLE, KNEE, PELVIS AND NECK INJURIES IN PEDESTRIANS AND IN CYCLISTS ACCORDING TO THE DIRECTION OF IMPACT AND TYPE OF VEHICLE

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ABSTRACT

In 683 pedestrian and 124 cyclist fatal victims the mechanisms of ankle, knee, hip, pelvis, cervical spine and neck muscles injuries were evaluated. The typical patterns of injuries were determined according to the direction of impact and the type of vehicle. The findings showed the relation between the direction of impact, the shape of vehicle's body and the mechanism of injuries found at the individual "levels" of the osteoarticular system. The results of the study may be used for forensic reconstruction of the circumstances of road traffic accidents, for diagnosis and treatment of pedestrians who survived and for validation of crash test results.

Key words: accident reconstructions, biomechanics, cadavers, pedestrians, bicycles

TRAFFIC ACCIDENTS are nowadays the most common causes of traumatic deaths and disability all over the world. In 2000, about 1.26 million people were killed due to road traffic accidents and by the year 2020, according to WHO forecasts, this figure is projected to nearly double making traffic accidents the third leading cause of death and disability worldwide (following ischaemic heart disease and mental depression). Despite a smaller total number of cars and accidents in developing countries (as well as countries of Eastern Europe), the percentage of fatalities is much greater than in the high-income countries (Table 1), which is strictly connected with a large number of non-motorised victims involvement mainly caused by lack of road infrastructure and no separation of pedestrian, bicycle and car streams (UN, 2002, World Bank, 2003, ACEA, 2003, IRTAD, 2003).

Country	Accidents per 100,000 population	Persons killed per 1000 accidents	Percentage of car-to-pedestrian accidents	Percentage of pedestrians in fatal victims	Percentage of cyclist in fatal victims
USA	77	20	3.7	11.3	1.6
Japan	74	30	n.a.	28.8	12.2
Austria	52	23	10.7	14.3	6.4
Belgium	48	30	7.0	9.7	9.1
Germany	47	20	9.3	13.2	8.8
Great Britain	40	15	17.3	25.1	3.7
Italy	37	30	7.3	13.2	5.8
European Union	34	31	11.7	14.6	5.3
Spain	26	57	12.5	15.5	1.5
France	21	63	14.7	10.4	3.3
Sweden	18	37	9.9	12.4	8.0
Poland	15	110	35.6	35.8	12.2
Russian Fed.	11	188	48.6	44.1	2.4

Table 1 - International rates of road traffic accident victims in 2000 (source: ACEA, IRTAD, UN)

Moreover, the statistical data reveal rapid changes in the structure of a vehicle fleet (ACEA, 2003). In 2003 in USA, "light trucks" constituted 35% of the motor vehicle fleet and were involved in 50% of road crashes (BTS, 2001). However, as yet "light commercial vehicles" have been rarely included in biomechanical studies (Niewöhner and Berg, 2001, Lefler and Gabler, 2001, Liu et al., 2002).

Since the issue of road traffic accidents intensifies, the studies concerning injuries to road traffic users become more and more important. It is well known that the injuries in pedestrians occur in different phases of accidents due to various forces acting:

- direct (shearing, crushing)
    - bumper (primary) injuries
    - secondary injuries (impact to hood, windshield or roof)
    - tertiary injuries (impact to the surface, shoulder or bank of road)
    - quaternary injuries (run over by the same or other vehicle)
- indirect (tearing, avulsion)
    - due to bending forces (e.g. knee and ankle injuries)
    - due to inertia force (e.g. neck injuries)

Those mechanisms may be used by specialists of various fields (e.g. car manufacturing, traumatology, forensic medicine) to:

- improve passive safety of vehicles
- improve the methods of diagnosis and treatment of injuries
- reconstruct and evaluate for litigious purposes the circumstances of accidents

It is essential that the effects of real world accidents (evaluated by means of suitably planned prospective studies carried out in large and uniform samples) should provide some reference point for validation of other methods (crash tests, computer simulations).

PURPOSE OF THE STUDY

The present paper is a continuation of prospective studies performed in the Department of Forensic Medicine, Medical University of Lublin since 1996, which concern the issues of widening the post-mortem diagnostic methods in victims of road traffic accidents used so far by examining the injuries to various "levels" of the locomotor system (Teresiński and Mądro, 2001a-c, 2002, Mądro and Teresiński, 2001).

The first stage of those studies was completed in 1999. The analysis of post-mortem results of 371 pedestrian victims of road traffic accidents defined the body areas whose injuries were most useful for reconstructing the victim-vehicle relation in the first phase of impact as they reflected the direction of forces (direct or indirect) acting when the most protruding elements of the vehicle hit the victim's body.

At present, an attempt was made to correlate the mechanism of injuries distinguished earlier (ankle, knee, hip, sacroiliac joints, sternocleidomastoid and scalene muscles and cervical spine ligaments) with the direction of direct and inertia forces which depend on the side of impact against the pedestrian's or cyclist's body and the shape of vehicle bodies in an over twice larger sample (including cyclists).

MATERIAL

In the years 1996-2002, 683 autopsies of pedestrian cadavers (widened by full preparation of soft tissues of the dorsum and limbs and by evaluation of the osteoarticular system of the lower limbs, pelvis and (in most cases) cervical spine) were performed in the Department of Forensic Medicine, Medical University of Lublin. Further analysis did not include those cases in which:

- the vehicle was not determined (hit-and-run accidents)
- the pedestrian was hit in the other than standing position (lying, kneeling, squatting etc.)
- the victim was hit by the motorcycle, bicycle or other atypical vehicle
- the hit was atypical (sideswipe, with a side-view mirror, etc.)
- the hit was oblique and the dominant direction impossible to be defined
- circumstances of the accident were not determined (inconsistent evidence, no files available, secondary run-over masking the injuries sustained on impact in the erect position)
- the victim's age < 14 years

In this way 466 typical cases were selected in which the pedestrians in the standing position were hit by the car's front and the circumstances of accidents could be explicitly defined. The victims < 20 constituted 7.7%, 20.9% were between 20-39, 34.7% - 40-59, 27.4% - 60-79 and 9.3%- 80-95 years old.

Since 1999 the same range of routine post-mortem examinations has started to be carried out in cyclists (previously such examinations were only performed in the cases in which it was initially unclear whether the victim was a cyclist or a pedestrian walking with his bike). The study included the autopsy results of 113 cyclists selected from 124 cases examined (a significantly lower percentage of "exclusions" than in the pedestrian group resulted from the fact that circumstances of hits were more likely to be explicitly determined on the basis of the bicycle damage).

METHODS

The cases were divided according to the direction of impact (front, rear, left or right side), which was defined on the basis of the location of injuries on autopsy and the files received from the Public Prosecutor's Offices (they contained scene and car inspection protocols with schemes and photos, automotive expert opinions and relations of witnesses). Each of the 4 selected groups was further divided into 3 subgroups according to the type of vehicle. Beside two usually described groups of passenger cars (with trapezoidal, pontoon or wedge bodies) and box-shaped lorries and buses (with high and flat front), we distinguished the third subgroup of delivery vans ("transporters"), which are extremely popular in Poland.

The examinations of individual "levels" of the skeleto-muscular system (ankle, knee, hip joints, pelvis and neck) and classifications of injuries were performed according to the methods described in the previous papers (Teresiński and Mądro, 2001 a-c, Mądro and Teresiński, 2001) and presented in Figures 2-4. The mechanisms were found by injury analysis and not by reconstruction of the body movement. In each of 9 selected subgroups (according to the direction of impact and type of vehicle) we compared the mechanisms of injuries to ankle joints (pronation, supination, dorsal and plantar flexion), knee joints (hyperextension, anterior tibial translocation, varus and valgus flexion), hip joints (central fractures, bruises on the section of the greater trochanter), sacroiliac joints (uni- and bilateral disruptions), the cervical spine (flexion, extension or lateral flexion) and sternocleidomastoid and scalene muscles (uni- and bilateral bruises in their lower attachments).

Similar methods were used to analyse the cyclist hits, however the vehicles were divided only into passenger cars and "others" as the number of cases was insufficient.

The study has not discussed the issue of impact speed evaluations because a vast majority of cases concerned high-velocity hits (impact speed > 50-60 km/h).

KNEE INJURIES : The analysis included only the cases subjected to examinations with the sections of epiphyses to detect bone bruises which in many cases were the only injuries found in the joint. Earlier studies (Teresiński and Mądro, 2001b) revealed that evaluation of injury mechanisms based only on the injuries to bone and ligament structures (without epiphysis sections) often led to improper conclusions and in many cases only sections of epiphyses showed the places of epiphysis compression and ligament avulsion (Fig.1). Moreover, bone bruises are extremely difficult to reconstruct in experimental conditions with post-mortem human subjects (PMHS) as blood circulation is a prerequisite of their development and microfractures of bone trabeculas (responsible for bone bruising) are macroscopically invisible (Ragger, 1998).

The knee joint injuries form patterns (Fig. 2) depending on the direction of the external force and pathological dislocation (bending) of joint structures (the risk of injury is the highest when the knee is blocked in full extension). Moreover, the injuries to ligamentous structures may result from shearing forces (due to dislocation of tibial and femoral diaphyses in the perpendicular plane). However, in real world the "isolated" mechanism of dislocation hardly ever occurs (the isolated cruciate ligament injuries in lateral and medial impacts were extremely rare) as initial shearing forces effects are "masked" by dominant "bending injures" (Teresiński and Mądro, 2001b, Bhalla et. al., 2003). The only exception are isolated anterior cruciate ligament (ACL) injuries in hits from rear caused by anterior dislocation of proximal tibia in relation to femoral condyles (Fig. 2) because the subsequent bending forces act in the natural range of articular movements ("pure" shearing effect).

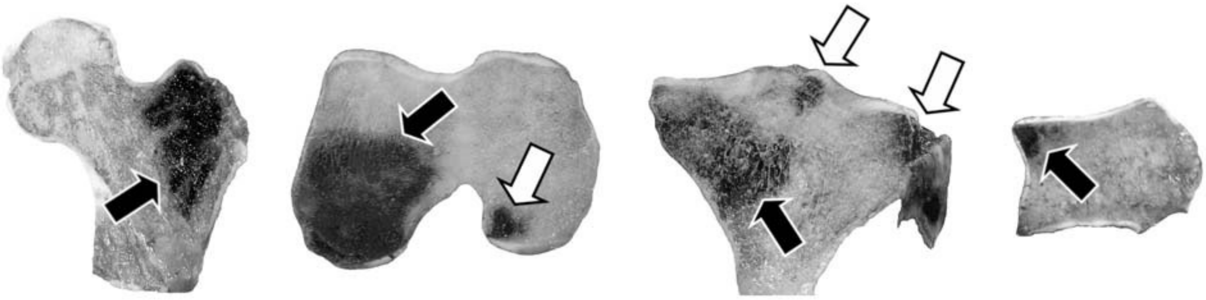

Fig. 1 - Bone bruises on frontal sections of femoral greater trochanter, femoral and tibial epiphyses and trochlea tali (white arrows – ligament avulsion, black arrows- epiphysis compression)

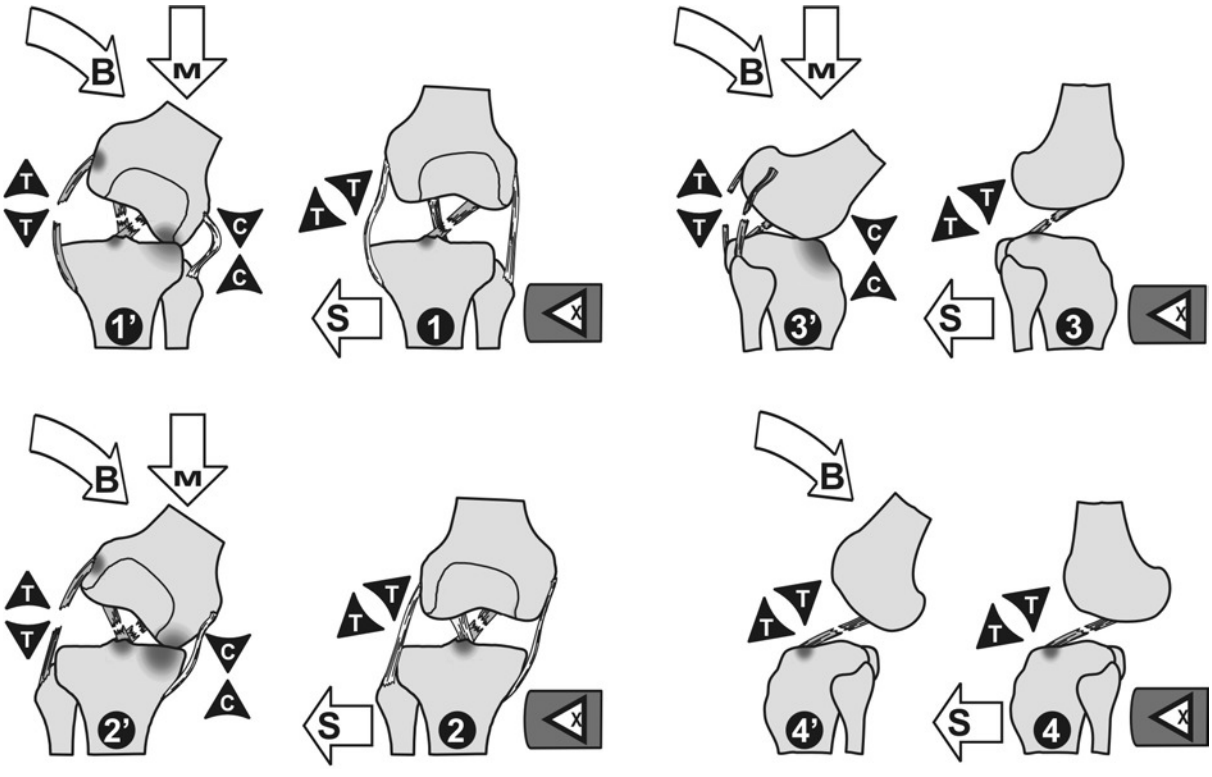

Fig. 2 – The main mechanisms of knee joint injuries and the phases (1→1', 2→2', 3→3', 4→4') of shearing (S) and bending (B) force acting in car-to-pedestrian accidents: 1' - valgus flexion, 2' - varus flexion, 3' - hyperextension, 4 - tibial anterior dislocation (T - tearing force, C - compression force, M - limb load by body mass, X - impact direction)

Generally, the forces tearing the ligamentous structures (avulsion) act on one side of the joint while those crushing the bone on the other one (however, the effects of these both components were not always detectable simultaneously). In many cases, the only symptoms of avulsion of ligaments were the bruises within their area (provided that effects of direct trauma in surrounding tissues were absent). On evaluation of the mechanism of joint injuries, bone bruises were found to be very useful, yet it was necessary to differentiate those caused by compression of the condyles from those resulting from tearing forces. The former were usually extensive, located in the central and deep condyle structures and reached under the articular surfaces of femoral and tibial condyles; they were sometimes accompanied by macroscopically visible fractures of articular surface, occasionally with indented or lowered level of the condyle. On the other hand, the bone bruises resulting from the avulsion mechanism were usually small* and located peripherally in the lateral parts of condyles (in the region of capsule attachments and collateral ligaments) or under the intercondylar eminence (in cruciate

* they may spread in the cases of longer survival

ligament avulsion); they were often accompanied by tearing off of small bone fragments at the place of ligamentous attachments. Bone bruises were regarded as more important than ligamentous injuries in assessing the mechanism of injury; the cases with inconsistencies between "equal" indicators were assigned as non-characteristic.

ANKLE INJURIES : similarly to the knee joint cases, the ankle injuries form patterns (Fig. 3) according to the direction of the external force and pathological dislocation of joint structures (Teresiński and Mądro, 2001a). Contrary to typical ankle "sprains" caused by improper positioning of the foot during running, jumping or skidding, the pedestrian victims of traffic accidents usually lack the axial rotation component and their injuries are caused by the forces acting only in one plane. It is characteristic that in the first phase of all types of trauma, the injuries are usually caused by tearing forces (Table 2) while in further phases by compressive forces (the limb must be loaded by body mass). The site of compression may be indicated by bone bruises on the section of the trochlea tali whose edges press the lateral (pronation) or medial (supination) malleolus (Fig. 1). Avulsion of collateral ligaments may result in disruption of the ligament or tearing off of its attachment or the whole malleolus. Due to the lack of ligaments strengthening the front and back of the joint capsule, the avulsion of anterior or posterior edges of the tibial distal epiphysis are rare (in the examined group the edge fractures were always caused by the compression mechanism).

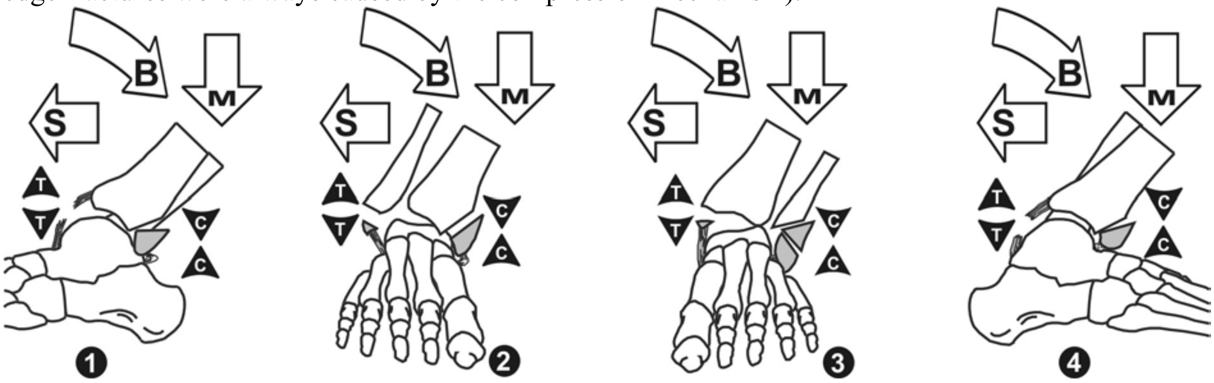

Fig. 3 - The main mechanisms of pathological dislocation of bone structures within the ankle joint: 1 – plantar flexion, 2 – supination, 3 - pronation, 4 - dorsal flexion (S - shearing force, B – bending force, T - tearing force, C - compression force, M - limb load by body mass)

Injury mechanism	avulsion phase	compression phase
Supination (inversion)	horizontal fracture of lateral malleolus at or below the level of articular space or rupture of lateral malleolus ligaments	vertical fracture of medial malleolus
Pronation (eversion)	horizontal fracture of medial malleolus or rupture of deltoid ligament	oblique fracture of lateral malleolus just above the level of ankle joint, often with displacement of a triangular fragment from the lateral surface of fibula
Dorsal flexion	tearing off of the posterior joint capsule	fracture of the anterior tibial edge
Plantar flexion	tearing off of the anterior joint capsule	fracture of the posterior tibial edge

Table 2 – The main mechanisms of ankle joint injuries in the victims of traffic accidents.

HIP INJURIES : in the injuries to the lateral side of the greater trochanter, the victims may sustain central fractures of the hip joint (or central dislocations when the femoral head is translocated into the interior of the pelvis) and bone bruises within it (Fig. 1) or (less frequently) femoral head (Teresiński and Mądro, 2001c).

NECK INJURIES : The injuries to the cervical spine ligaments result mainly from rapid flexion of the neck in the anterior, posterior or lateral direction (Fig.4) caused by inertia forces or direct trauma of the head (Mądro and Teresiński, 2001). This is also likely to tear off the muscles, which is visible as bruises around their attachments (less frequently along them).

The cases subjected to subclavicular injections or those with fractures of upper ribs and clavicles were excluded (due to secondary bruises).

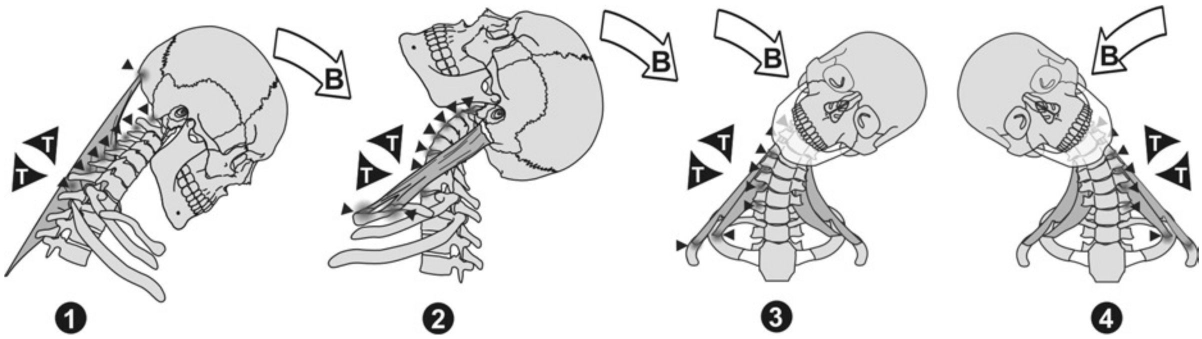

Fig. 4 - The main mechanisms of injuries to the cervical spine ligaments and lower insertions of neck muscles: 1 – flexion (nape muscles shown), 2 – extension (left sternocleidomastoid shown), 3, 4 – lateral flexion (scalene muscles shown), T - tearing force, B – bending force

RESULTS AND DISCUSSION

PEDESTRIANS : the tables 3-9 present the results of analysis of the frequency of injuries to ankle, knee, hip, sacroiliac joints, cervical spine, sternocleidomastoid and scalene muscles according to the type of vehicle and direction of impact.

The analysis of the cases showed the most typical patterns of injuries to the examined locomotor structures (Table 10). Moreover, it turned out that lorries and buses (but almost exclusively those “old ones” - with high bumpers) frequently caused “reversed“ injuries to ankle and knee joints compared to those caused by passenger cars (lever principle), e.g. knee hyperextension was the marker of front hits by passenger cars and back hits by lorries. The mechanism of pelvic injuries, on the other hand, did not depend on the type of vehicle, e.g. ipsilateral sacroiliac joint disruption (the majority of bilateral disruptions resulted from secondary running over).

Compared to passenger cars and lorries, delivery vans often caused “transitional” injury patterns, i.e. “reversed” complexes only at the level of ankle joints. However, this correlation concerned mainly typical “transporters” of box-shaped bodies (with the flat but quite low bonnet contour and retreated windscreen - e.g. Transit, Ducato, Sprinter).

ankle	Impact side											
	from front			from rear			from lateral			from medial		
Vehicle type	PA	DV	LB	PA	DV	LB	PA	DV	LB	PA	DV	LB
Number of examined victims	29	6	2	84	12	21	233	30	25	233	30	25
Number of victims with ankle injuries	10	1	0	36	3	6	123	13	8	123	13	8
Number of damaged joints [a]	10	1	0	47	4	8	80	10	6	81	7	4
Mechanism of injury												
supination	1	0	0	4	0	2	5	4	**5**	**66**	3	2
pronation	1	0	0	8	1	0	**67**	4	1	7	3	1
plantar flexion	0	1	0	**30**	0	0	3	0	0	3	1	0
dorsal flexion	**6**	0	0	0	**3**	**4**	1	0	0	1	0	0
non-characteristic	2	0	0	5	0	2	4	2	0	4	0	1

Table 3. – Frequency of ankle joint injuries in pedestrian victims depending on the direction of impact and type of vehicle (PA – passenger cars, DV – delivery vans, LB – lorries and buses; a - only ipsilateral joints in lateral and medial hits)

knee	Impact side											
	from front			from rear			from lateral			from medial		
Vehicle type	PA	DV	LB	PA	DV	LB	PA	DV	LB	PA	DV	LB
Number of examined victims	25	5	1	59	11	15	221	30	19	221	30	19
Number of victims with knee injuries	25	5	0	46	8	11	212	29	16	212	29	16
Number of damaged joints [a]	46	8	0	65	10	16	162	26	12	171	16	9
Mechanism of injury												
varus flexion	0	0	0	7	2	1	7	1	**5**	**140**	**10**	3
valgus flexion	1	0	0	4	0	3	**125**	**23**	3	7	1	3
dislocation [b]	1	0	0	**27**	3	0	5	0	0	3	1	0
hyperextension	**40**	**8**	0	8	1	**11**	2	0	0	7	1	0
non-characteristic	4	0	0	19	4	1	23	2	4	14	3	3

Table 4. – Frequency of knee joint injuries in pedestrian victims depending on the direction of impact and type of vehicle (PA – passenger cars, DV – delivery vans, LB – lorries and buses; a - only ipsilateral joints in lateral and medial hits; b - anterior dislocation of proximal tibia in relation to femoral condyles - isolated ACL injury)

hip	Impact side								
	from front			from rear			from lateral		
Vehicle type	PA	DV	LB	PA	DV	LB	PA	DV	LB
Number of examined victims	19	5	0	45	9	13	167	23	18
Number of victims with hip injuries [a]	1	0	0	0	0	1	17	4	5
ipsilateral	-	-	-	-	-	-	**17**	**4**	**4**
contralateral	-	-	-	-	-	-	0	0	0
bilateral	0	0	0	0	0	0	0	0	1

Table 5 – Frequency of hip joint injuries in pedestrian victims depending on the direction of impact and type of vehicle (PA – passenger cars, DV – delivery vans, LB – lorries and buses; a - central fractures and/or bone bruises on great trochanter cross-sections)

pelvis	Impact side								
	from front			from rear			from lateral		
Vehicle type	PA	DV	LB	PA	DV	LB	PA	DV	LB
Number of examined victims	30	6	2	93	14	22	243	30	26
Number of victims with pelvis injuries									
Number of victims with sacroiliac joints injuries	5	0	0	6	1	3	67	7	8
ipsilateral	-	-	-	-	-	-	**50**	**6**	**5**
contralateral	-	-	-	-	-	-	4	1	2
bilateral	2	0	0	0	1	0	13	0	1

Table 6 – Frequency of sacroiliac joint injuries in pedestrian victims depending on the direction of impact and type of vehicle (PA – passenger cars, DV – delivery vans, LB – lorries and buses)

The mechanism of knee injuries in passenger car (especially small and compact type – dominant in Poland) hits showed high “tolerance” to the differences in pedestrians` height – the cases of “reversed” knee injuries caused by very low hits at the level of distal shins (e.g. a tall victim hit by the low-suspended and severely braking passenger car with the wedge-shaped body) were extremely rare. In short victims the passenger car hits were similar to those caused by delivery vans (i.e. “reversed” complexes of injuries at the ankle level – especially in large passenger car hits).

cervical spine	Impact side								
	from front			from rear			from lateral		
Vehicle type	PA	DV	LB	PA	DV	LB	PA	DV	LB
Number of examined victims	20	5	3	59	9	16	156	25	12
Number of victims with cervical spine injuries	13	4	1	29	7	6	81	11	4
Mechanism of injury									
flexion	**8**	1	0	2	2	2	18	2	1
extension	0	0	0	**18**	3	2	7	2	0
lateral flexion	1	1	0	3	1	0			
ipsilateral	-	-	-	-	-	-	4	2	**3**
contralateral	-	-	-	-	-	-	**41**	2	0
non-characteristic [a]	4	2	1	6	1	2	11	3	0

Table 7 – Frequency of cervical spine injuries in pedestrian victims depending on the direction of impact and type of vehicle (PA – passenger cars, DV – delivery vans, LB – lorries and buses; a – mainly complete spine disruption without lateralisation)

sternocleidomastoid	Impact side								
	from front			from rear			from lateral		
Vehicle type	PA	DV	LB	PA	DV	LB	PA	DV	LB
Number of examined victims	14	5	1	54	8	14	129	21	10
Number of victims with sternocleido-mastoid injuries	3	1	0	12	3	2	34	4	2
ipsilateral	-	-	-	-	-	-	6	0	**2**
contralateral	-	-	-	-	-	-	**21**	2	0
bilateral	1	0	0	**9**	2	2	7	2	0

Table 8 – Frequency of sternocleidomatoid injuries in pedestrian victims depending on the direction of impact and type of vehicle (PA – passenger cars, DV – delivery vans, LB – lorries and buses)

scalene muscles	Impact side								
	from front			from rear			from lateral		
Vehicle type	PA	DV	LB	PA	DV	LB	PA	DV	LB
Number of examined victims	12	4	1	48	8	11	113	16	8
Number of victims with scalene muscles injuries	5	0	0	9	5	1	24	5	4
ipsilateral	-	-	-	-	-	-	0	0	**4**
contralateral	-	-	-	-	-	-	**22**	**4**	0
bilateral	**5**	0	0	**6**	5	1	2	1	0

Table 9 – Frequency of scalene muscles injuries in pedestrian victims depending on the direction of impact and type of vehicle (PA – passenger cars, DV – delivery vans, LB – lorries and buses)

In the group of pedestrians hit by passenger cars from a side who sustained fractures of diaphyses of only one shin, the knee injuries were paradoxically more common and more severe (in AIS scale, 1998) in the limb which was not broken (despite the fact that axial loading was theoretically greater in the other limb to produce the fracture). This correlation was found to be statistically significant ($P<0.05$, Wilcoxon test for dependent data pairs) and is consistent with the experimental findings (Cesari et al., 1989, Kajzer et al., 1997, Takahashi et al., 2000, Bhalla et al., 2003).

Level	Vehicle type	Impact side			
		from front	from rear	from lateral	from medial
Ankle	passenger cars	dorsal flexion	plantar flexion	pronation	supination
	delivery vans	plantar flexion	dorsal flexion	supination	pronation
	trucks and buses	plantar flexion?	dorsal flexion	supination	pronation?
Knee	passenger cars	hyperextension	translocation [a]	valgus flexion	varus flexion
	delivery vans	hyperextension	-	valgus flexion	varus flexion
	trucks and buses	-	hyperextension	varus flexion	valgus flexion
Hip	passenger cars	-	-	ipsilateral injury [b]	
	delivery vans	-	-	ipsilateral injury [b]	
	trucks and buses	-	-	ipsilateral injury [b]	
Pelvis	passenger cars	-	-	ipsilateral sacroiliac joint damage	
	delivery vans	-	-	ipsilateral sacroiliac joint damage	
	trucks and buses	-	-	ipsilateral sacroiliac joint damage	
Neck	passenger cars	flexion	extension	lateral flexion (contralateral damage)	
	delivery vans	flexion	extension	lateral flexion (contralateral damage)	
	trucks and buses	extension?	flexion?	lateral flexion (ipsilateral damage)	

Table 10 - The most common mechanisms of ankle, knee, hip, pelvis and neck injuries in pedestrian hits caused by the vehicles of different car-body shapes (a - isolated injury to the ACL due to anterior translocation of the proximal tibial epiphysis in relation to the femoral condyles; b – central fracture of acetabulum or/and bone bruises within greater trochanter).

CYCLISTS : although the number of cyclists examined by us was too small to conduct full analysis with the division of vehicles into 3 groups as it was done in pedestrians (some injury patterns were found in a too small number of cases to be conclusive), some regularities were distinguished:

- similarities between car-to-pedestrian and car-to-bicycle hits:
    - the mechanism of neck injuries in cyclists was similar to that in pedestrians hit by passenger cars
    - the mechanism of pelvis injuries in lateral hits was similar in cyclists and pedestrian groups (ipsilateral damage to sacroiliac joints)
    - in lateral impacts the most common mechanisms of knee injuries in cyclists were the same as those observed in the pedestrian hits caused by passenger cars
    - in lateral and rear impacts the most common mechanisms of ankle injuries in cyclists were the same as those observed in the pedestrian hits caused by passenger cars
- differences between car-to-pedestrian and car-to-bicycle hits:
    - the examined injuries were generally less frequent in cyclists than in pedestrians
    - the mechanism of neck injuries in cyclists was independent of the type of vehicle (no "ipsilateral" flexion injuries as in pedestrians hit by lorries and buses)
    - within the knee joints in cyclists hit from the front and back passenger cars often caused "reversed" injuries (compared to the mechanism in pedestrians), e.g.:
        - hyperextension was found to be the marker of back hits in cyclists (it occurred in 21 out of 33 damaged joints) - contrary to pedestrian hits in which hyperextension occurred as a rule in frontal hits
        - in frontal hits, passenger cars usually did not cause any typical knee injuries in cyclists - contrary to pedestrians hits in which the hyperextension injuries were almost exclusively observed
        - the hyperextension mechanism was common in the cases of cyclists hit from the front by box-type vehicles (in 4 out of 5 damaged joints)
    - the haemorrhages within the subcutaneous tissue of the medial proximal surfaces of thighs (and the scrotal sac in men) were about 3 times less frequent in pedestrians than

in cyclists (in whom they occurred in approximately 1/4 of cases probably due to contact with a saddle*).

The above findings led to a compilation of the most probable patterns of injuries in cyclists hit by passenger cars and other box-shaped vehicles (Table 11).

Level	Vehicle type	Impact side			
		from front	from rear	from lateral	from medial
Ankle	passenger cars	dorsal flexion?	plantar flexion	pronation	supination
	box-shaped vehicles	plantar flexion?	?	-	-
Knee	passenger cars	-	hyperextension	valgus flexion	varus flexion
	box-shaped vehicles	hyperextension	-	?	?
Hip	passenger cars	-	-	ipsilateral injury [a]	
	box-shaped vehicles	-	-	ipsilateral injury [a]?	
Pelvis	passenger cars	-	-	ipsilateral sacroiliac joint damage	
	box-shaped vehicles	-	-	ipsilateral sacroiliac joint damage	
Neck	passenger cars	flexion	extension	lateral flexion (contralateral damage)	
	box-shaped vehicles	flexion?	extension	lateral flexion (contralateral damage)	

Table 11 – Probably the most common mechanisms of ankle, knee, hip, pelvis and neck injuries in cyclist hits caused by passenger cars and box-shaped vehicles (a – central fracture of acetabulum or/and bone bruises within greater trochanter).

CONCLUSIONS

Numerous studies have already been carried out concerning the injuries in non-motorized victims of road traffic accidents. However, they usually dealt with their frequency or AIS grading rather than mechanisms or circumstances in real world. On the other hand, the collision tests performed with PMHS do not allow to detect the injuries which occurred only intravitally (bone bruises, haemorrhages in the attachments of ligaments and cervical muscles) and are essential to define the injury mechanism. Therefore, the present paper seems to be the first one which describes thoroughly the relations between the shape of vehicle's body, direction of pedestrian's or cyclist's hit and mechanisms of injuries to the lower limb joints, pelvis and neck. Moreover, the distinguished mechanisms of injuries to joint structures show the differences between the pedestrian's body „behaviour" (especially with relation to the direction of neck and shin bending) on impact in high-speed real world accidents and in computer simulations (as well as PMHS tests), which additionally do not always take into account the effects of „dipping" of the vehicle front during intensive braking before the hit (Eubanks, 1998, Moser et al., 1999, Rau et al., 2000, McLundie, 2003, Rooij van et al., 2003).

For many years the efforts of researchers and car companies have been focused on the issue of reducing the degree of trauma in traffic accident victims (EEVC, 1998, NCAP, 2003). The changes in bumper construction and spreading of impact energy over larger surface undoubtedly decreased the number of lower extremity fractures in pedestrian hits. Unfortunately it seems, that "redistribution" of impact energy paradoxically increases the risk of injuries to the joint structures which from the medical point of view are more dangerous than even multi-site diaphyseal fractures because the ligament injuries more often result in permanent disability (although both are usually non-fatal). The low, protruding and inflexible bumpers in old vehicles as a rule caused fractures of the shins which paradoxically protected the knee joints against major trauma concentrating and absorbing the impact energy. However, from the forensic expert's point of view, high percentage of knee joint injuries in present pedestrian hits provides a big chance of reconstruction of the accident on the basis of the mechanism of trauma.

* In the cases of oblique passenger car-to-bicycle hits (usually at angles lower than 30º) the cyclist's thighs and buttocks rotate the saddle opposite the impact site while in hits close to perpendicular the saddle rotates towards the striking vehicle (Wegner et al., 2000)

The present findings showed the relation between the direction of impact in pedestrians or cyclists, the shape of vehicle's body and the mechanism of injuries found at the individual "levels" of the osteoarticular system. In the first phase of an accident the victim's body „adjusts" to the shape of the vehicle front contour and the point of force application determines the way of pathological dislocation of joint structures thus determining the mechanism of ankle, knee and neck injuries.

The results of the study may be used in forensic reconstruction of the circumstances of road traffic accidents since the basic element of legal evaluation of an accident is to determine the direction of the pedestrian or cyclist movement in relation to the vehicle's path. It is also possible to differentiate the cyclist victims (riding their bicycles) from those who walked with their bicycles and to anticipate the type of vehicle in "hit-and-run" accidents. Moreover, the findings may be used in the diagnosis and treatment of victims who survived – e.g. to "predict" occult injuries (particularly in unconscious patients) providing that the circumstances of accidents are known.

Although the study was based on the autopsy material, its findings may be used to reconstruct the circumstances of accidents also in the survival cases. Many of the injuries examined may be detected intravitally using standard imaging techniques (X-ray, CT); additionally the MR imaging enables to detect bone bruises in the epiphyses (Mink et al., 1993, Hayes et al., 2000, Sanders et al., 2000). However, compared to the autopsy results, the frequency of injuries in living victims may vary due to the differences in collision velocity (though, the ankle and knee injuries are already found in pedestrian hits with very low speed as they result from the body mass action during pathological dislocation of the joint in the indirect mechanism).

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