10

Chapter 10

Injuries of the Thigh, Knee, and Ankle as Reconstructive Factors in Road Traffic Accidents

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1. Introduction

1.1. Global Burden of Traffic Accidents

Currently, traffic accidents comprise the most common cause of traumatic deaths throughout the world and the most common cause of death and disability in the 15- to 44-yr-old age group in developed countries. In 2002, about 1.2 million people were killed in road traffic accidents, and by the year 2020, according to WHO data *(1)*, this figure is projected to almost double, making traffic accidents the third (from the ninth) leading cause of death and disability worldwide (following ischemic heart disease and mental depression). Despite a large number of cars and accidents in high-income countries, however, the percentage of fatalities is low (Table 1). A good marker of the motorization progress in a particular country is the percentage of pedestrians among all victims of traffic accidents, e.g., high in the low-income countries and eastern Europe (due primarily to a lack of road infrastructure and the absence of a separation between pedestrian and car streams).

1.2. Legal Assessment of Traffic Accidents

1.2.1. The Need for Reconstruction

According to police statistics, only a small percentage of traffic accidents are the result of incidental factors or the poor conditions of vehicles. The most common causes of road collisions are errors by drivers and improper behavior of pedestrians who often are both the causes and victims of traffic accidents.

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Table 1
International Rates of Road Traffic Accidents in 2002 *(2)*

Country	Passenger Cars per 1000 Population	Road Traffic Accidents per 10,000 Population	Persons Killed per 1000 Accidents	Car-to-Pedestrian Accidents %
USA	776	69	22	3.9
Italy	583	41	28	6.7
Germany	541	44	19	9.3
Austria	494	54	22	11.0
France	492	18	69	14.8
Belgium	462	46	28	7.2
Sweden	452	19	33	9.4
Spain	455	24	54	11.8
Great Britain	448	39	15	16.9
Poland	289	14	109	33.7
Russian Federation	156	13	180	46.0

The basis of legal evaluation of the results of traffic accidents is the assessment of the participant's behavior and the road situation. To determine the degree of involvement of individual persons, traffic accidents should be reconstructed and testimony given by witnesses must be verified *(3–6)*. It is well known that when the driver is the only witness, he is likely to present the accident version that is more favorable for him (Fig. 1), e.g., a sudden intrusion of the pedestrian from the right side of the road at daytime and from the left lane at night (due to the light asymmetry and better lighting of the right side of the road). In car-to-bicycle accidents, depending on the road situation, the driver may claim that he hit the cyclist or the pedestrian walking with his bicycle.

Occasionally, the victim's body (injured or dead) is the only evidence available on which to base a reconstruction of the accident (e.g., in hit-and-run accidents and in the absence of other traces on the road or on the victim's clothes).

1.2.2. Reconstruction Parameters (Biological Markers)

From a medical point of view, a deduction of the circumstances of traffic accidents (e.g., determining the direction of hit or who was driving) depends on demonstrating certain injuries (biological markers) that reflect the type and direction of the external force *(7)*. Within more than 100 yr of motoring history, the evolution of vehicles has resulted in changes in the types of injuries sustained by victims, which, in turn, has made it necessary to consider new biological factors for reconstruction of the circumstances of accidents. For example, in the first decades of 20th century, the majority of fatalities from accidents involved pedestrians who were run over by vehicles with high bumpers that knocked pedestrians down after hitting them while they were in the erect position, thereby causing a secondary running-over of the victim. As the floor of the car was lowered and cars became fitted with low front bumpers, victims were thrown against the hood ("run under") and typical "bumper fractures" shifted typically to the shin diaphyses (the meaning of the term "bumper fracture" has also changed,

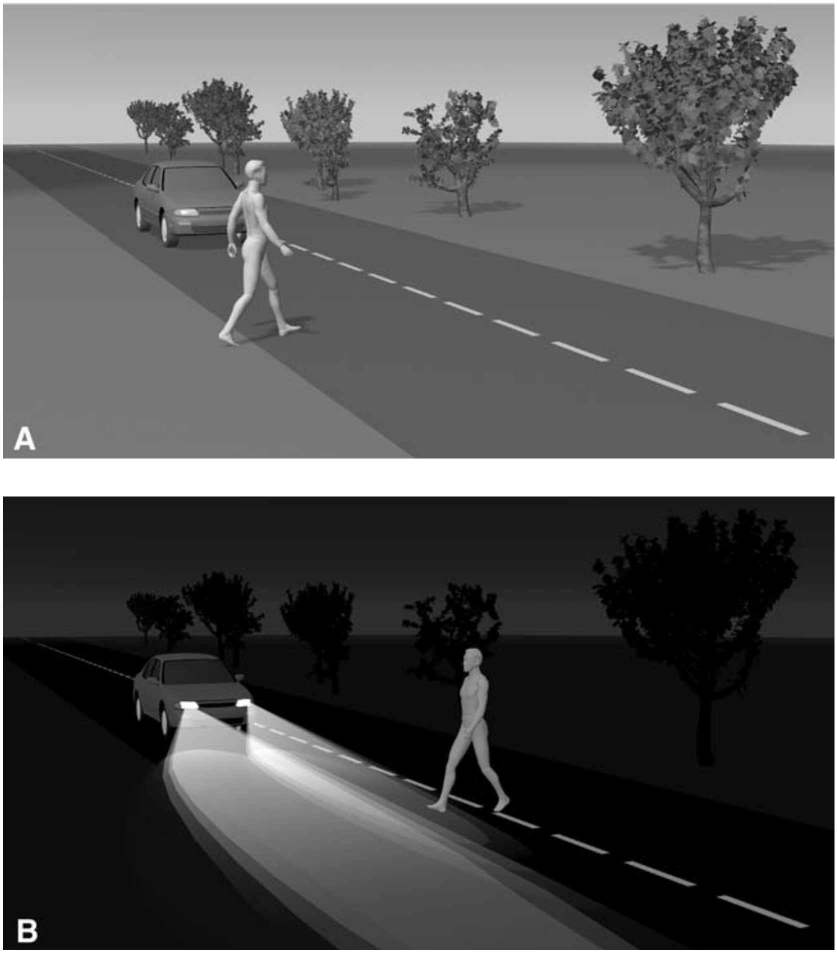

Fig. 1. The most dangerous directions of pedestrian intrusion by day and by night (the driver has the shortest time to react after noticing the pedestrian).

because it was first introduced during the 1930s by orthopedic surgeons as a synonym of tibial condyle fractures).

The biological markers for reconstruction must be associated with the first phase of the accident, i.e., the first contact with the victim's body by vehicular elements (e.g., "bumper injuries" in pedestrians and "dashboard injuries" in car occupants). The injuries should be detectable not only on autopsy but also by various imaging examinations in survivors.

1.2.3. Evidential Value of Biological Markers

From a legal point of view, each piece of evidence (both biological and technical) used in legal proceedings should be characterized by a precisely defined evidential value, especially by a strictly defined risk of error. Certain types of trauma will cause typical injuries only in some victims (this percentage makes it possible to make a deduction on the basis of a particular marker). Thus, from a medicolegal point of view, a lack of any typical injury often cannot be used as the evidence (negative), i.e., the exclusion of a mechanism and thus a deduction should be based only on "positive" evidence. The percentage of cases with a defined injury pattern that indicates a mechanism different from the presumed one is an error risk for this marker *(7)*.

1.2.4. A Key Role of Lower Extremity Injuries in Some Aspects of Post-Crash Expertise

In various types of traffic accidents, the lower extremities are the first to come in contact with the body or interior of the vehicle (not only in pedestrians but also in cyclists, motorcyclists, drivers, and car occupants), and the injuries observed provide the best chance of proper forensic reconstruction of trauma circumstances *(4–6)*. The following circumstances are especially pertinent to pedestrian hits:

- location of pedestrian toward vehicle
- standing or recumbent position (important in "hit-and-run" accidents)
- impact direction (walking direction)
- type of collision (front, corner, sideswipe)
- moving phase (standing or moving)
- type of vehicle (in "hit-and-run" accidents)
- whether the vehicle was braked
- course of individual phases, particularly in complicated cases (e.g., hits in the standing position hits with subsequent running over by one or more vehicles)

In car crashes, it is most important to determine who was driving and whether the victim was wearing a seat belt. In motorcycle crashes, it is pertinent to determine whether the victims was the driver or passenger; and in car-to-bicycle accidents, it is important to determine whether the victim was the bicyclist or a pedestrian (and whether the individual was riding or walking along with bike) and the direction of impact.

Lower-extremity injuries are particularly relevant in car-to-pedestrian hits because they reflect the actual location of the pedestrian relative to the vehicle on collision, whereas the trunk, upper extremities, and head of the victim indicate the upper parts of the car that hit the body later, when the victim's body had already been rotated (Fig 25). Of note, there is no reliable method for evaluating crash speed in terms of biological markers *(5)*.

2. Lower-Extremity Injuries Useful for Reconstruction of Accidents

2.1. External Injuries

During the early years of motoring, forensic experts had already addressed the injuries characteristic of the recumbent body being run over. However, regular tire imprints on the victim's body are rarely observed and occur only at low speeds (e.g., when the victim is run over by a vehicle that is backing up). Contrary to popular belief, the most common traces found only resemble tire marks or are completely noncharacteristic (Fig. 2). The parallel, concentrated striae-like skin ruptures resulting from excessive pressure may also indicate the rolling of the victim's body by the wheel (Fig. 3). However, these signs are not specific for runover cases and are also likely to be caused by hitting the pedestrian in the standing position, because the rapid movement of the lower extremities may lead to similar skin tensions and ruptures, especially in groin region *(3,8,9)*.

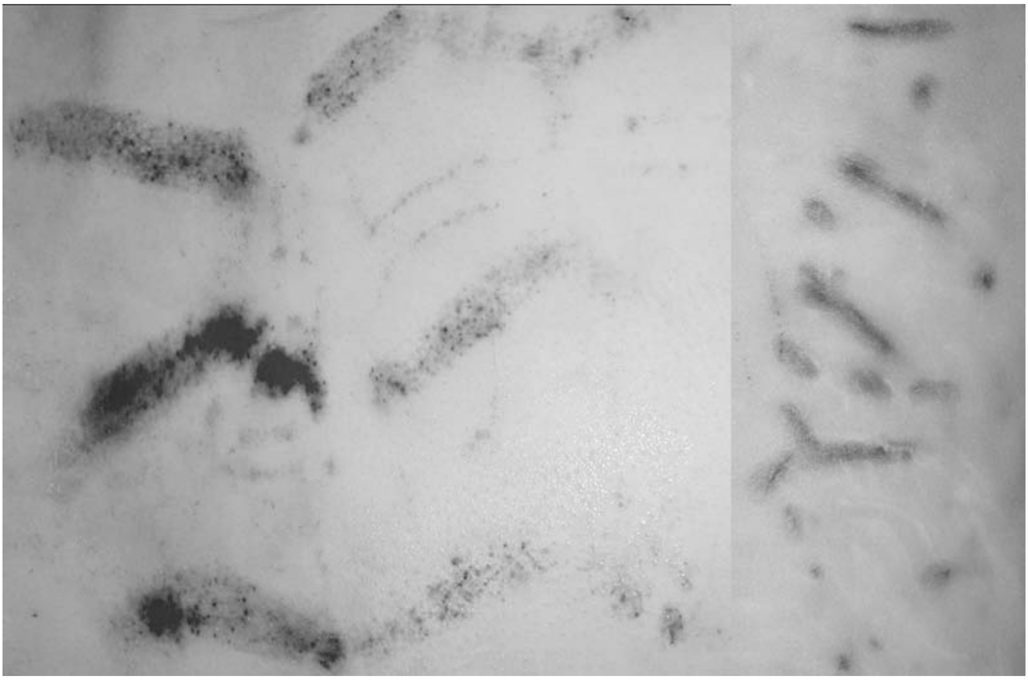

Fig. 2. Typical tire marks on the skin of victims run over by low- (left) and high-speed (right) vehicles.

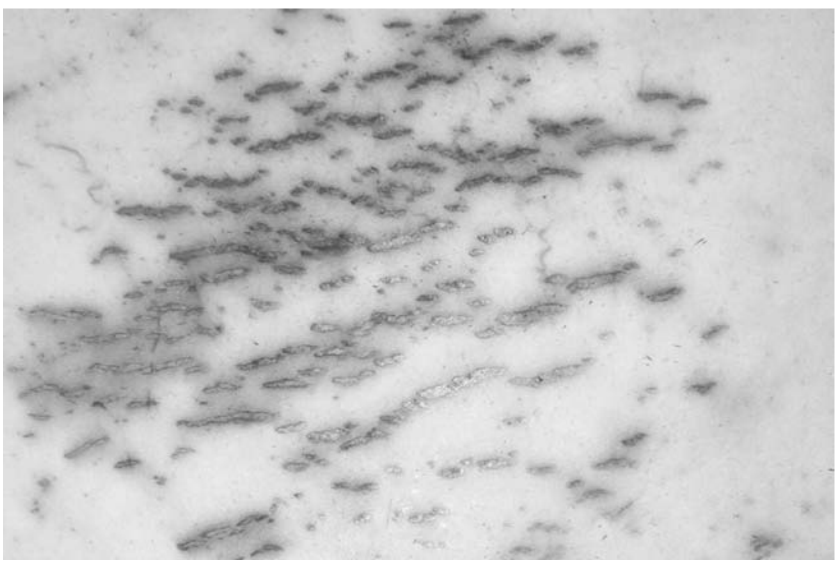

Fig. 3. Striae-like skin ruptures.

Until the 1970s, the reconstruction of impact direction in erect-pedestrian hits was based on a search for visible external "imprint" injuries, i.e. a "stamp" of the car's body elements on the victim's body (Fig. 4), similar to those observed in nonbelted car

Fig. 4. Imprint injuries in the pedestrian victim.

occupants when a bent knee hits the instrument panel (Fig. 5) *(3–5,9)*. However, the bodies (and interior) of modern vehicles are smooth, without edges or protruding elements and, thus, often do not cause any external injuries, even when internal injuries are extensive. Paint or dust chafing may be observed on the cloth of the trousers where the lower limbs contacted the car body (Fig. 6) *(4,9a)*. At present, the majority of external injuries (wounds, excoriations) found on the body of the pedestrian (or cyclist) victim are caused by further phases of the accident—impact and rubbing against the rough road surface (Fig. 7), rather than contact with the car body (except for those caused by glass chips). Only some open-extremity fractures are relevant for evaluation of the mechanism of injury *(9)* because the bone fragments often pierce the skin on the side opposite the injury (Fig. 8). If the victim dies directly after being hit, skin bruises are rarely observed; such bruises may occur in survivors, however, even few days after the injury due to the spread of deep bruises (*see also* Subheading 2.2).

2.2. Soft Tissue Injuries

Pedestrian- or cyclist-to-car hits usually cause extensive bruises and the crushing of deeper tissues, which can be detected within the organ by ultrasound and on autopsy only after extensive removal of the skin of the back and the entire circumference of extremities and deep-muscle incisions. In many cases, the location of bruises allows the investigator to determine the direction of impact and in hit-and-run accidents may also help the investigator determine the type of vehicle responsible for the injuries on the basis of the level at which bumper injuries are observed (Fig. 9). The injuries are usually located lower than the bumper level because the front part of the vehicle dips on braking.

Fig. 5. External injuries from a dashboard.

Fig. 6. Dust wipes on the bumper due to contact with both of the pedestrian's legs.

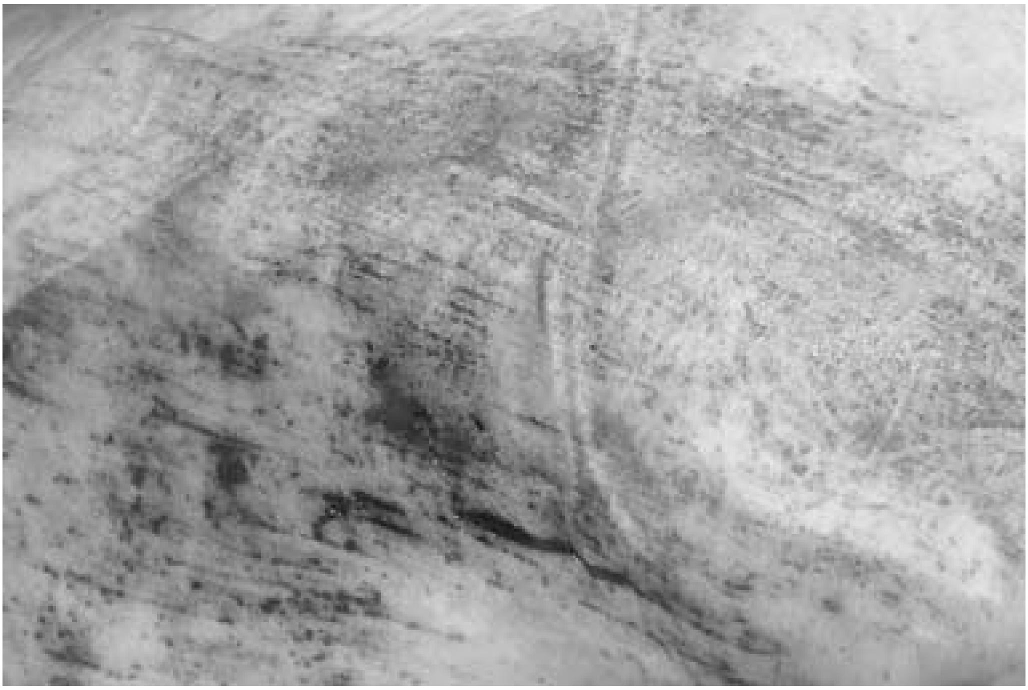

Fig. 7. Typical skin excoriations caused by being dragged along a rough road surface.

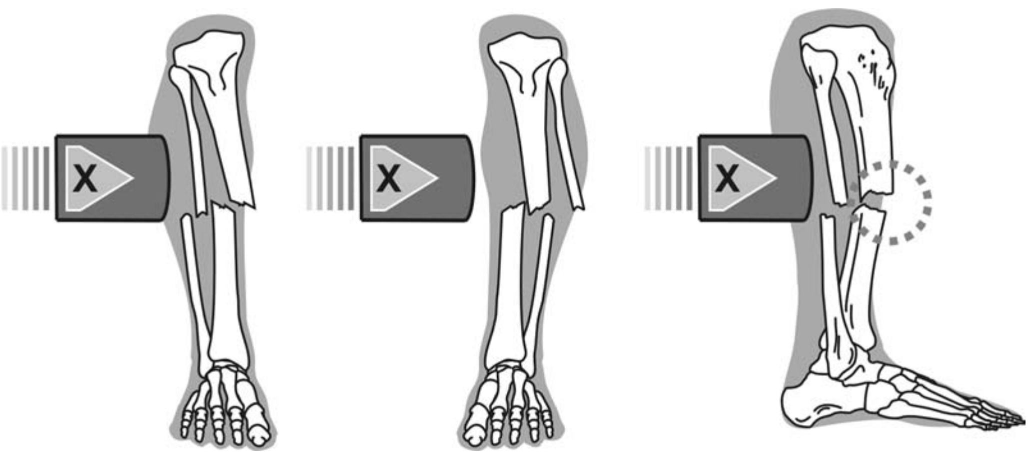

Fig. 8. Skin pierced by bone fragments on the side opposite to that on which the injury occurred (open fracture).

Moreover, heavy car loading and the height of the victim's shoes (especially important in women) may substantially lower the contact level. Injuries located only on one extremity may indicate that the victim was hit by the corner of the vehicle *(4,5,9)*.

Moreover, the skin preparation enables investigators to detect the areas in which the skin is torn from the muscle fascia as a result of the turning wheel rolling across the extremity ("decollement"); this usually involves most of the circumferences of the extremity (Fig. 10). Deeper injuries are usually more extensive on the side of the

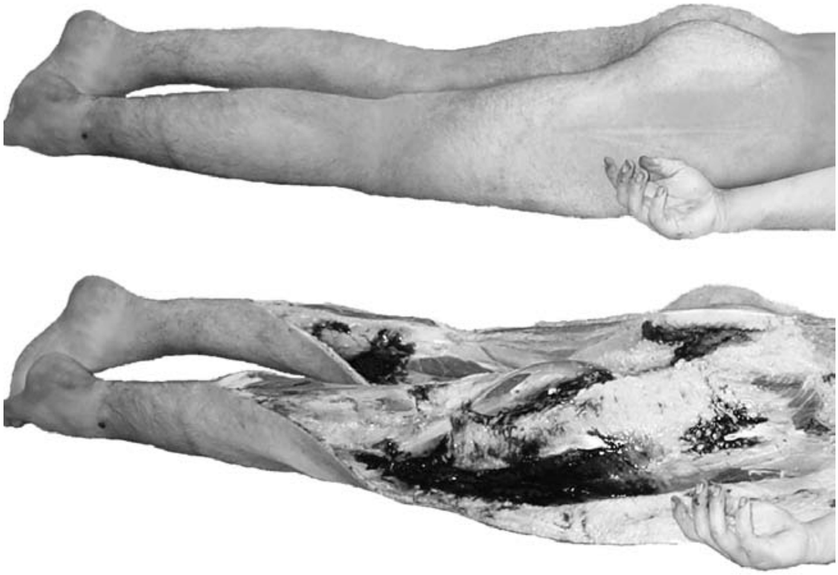

Fig. 9. Bruises in the muscles and subcutaneous tissue ("bumper injuries") revealed after skin preparation in the lower limbs.

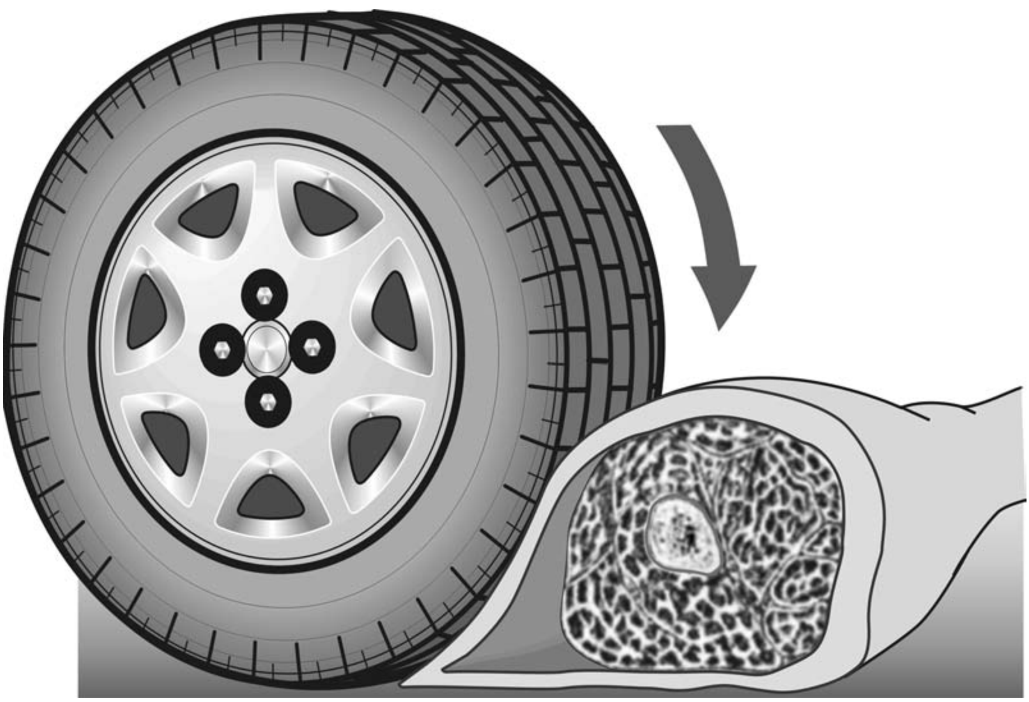

Fig. 10. The mechanism of the decollement type of skin detachment.

extremity towards which the vehicle was moving, and skin ruptures may lie transversely to the direction of the car. In most cases, however, the skin is not ruptured and a "subcutaneous pocket" forms, filled with blood and crushed fatty tissues *(3,5,9)*. Skin detachment is also likely to result from a tangential or oblique hit when the victim is in an erect position (when the corner or side of the vehicle only "brushes" the pedestrian's body) and occasionally by a perpendicular impact (especially in the elderly) as a result of the crushing of subcutaneous tissue, although in the latter case, they are usually much less extensive than in the cases involving being run over by the wheel *(10)*.

Modern vehicles are constructed to reduce the degree of traumatic injury in pedestrians by distributing the energy of primary trauma over larger surface area and by partially absorbing the energy into car body elements *(11)*. Therefore, in more and more cases typical "bumper injuries" cannot be detected or the "primary impact" injuries cannot be distinguished from secondary injuries occurring in subsequent phases of the accident. Such difficulties are even greater when the victim survives a relatively short time, because bruises tend to spread beyond their primary location within soft tissue; the infiltration of tissue with blood is particularly common around skeleton fractures, and bruises spread throughout (also due to gravity) loose connective tissue and interfascial spaces, especially when parenchymatous bleeding persists. In delayed postaccident deaths, which are increasingly common, the bruises undergo complete resorption before death.

2.3. Long-Bone Diaphyseal Fractures

Before the era of motorization, Messerer *(12)* had already performed experiments in long-bone diaphyseal fractures demonstrating that bones were less resistant to tearing than to compression forces. Thus, during bending, first the convex side of the bone is broken and fracture fissures run towards the concave side, forming a wedge-shaped bone fragment (Figs. 12, parts 1 and 2). During the 1960s, the rule formulated by Messerer concerning the so-called bending fractures—i.e., that the apex of the wedge-shaped fragment defines the direction of bending in bone—was adapted for use in reconstructing the direction of impact *(3,4,9,13)*. However, even a typical bending fracture, Messerer`s wedge indicates the direction of impact only when the bone was bent at the moment of impact, and not in a later phase of the accident.

Furthermore, bending fractures usually occur at a low speed of impact ("static" fractures; the lower the impact speed, the bigger the wedge base) *(14)*. At higher speeds of impact, "dynamic," noncharacteristic transverse or multifragment fractures are usually observed (more often in the elderly because of osteoporosis); in some cases, even "false" wedge-shaped fragments may be seen (i.e., the apex and not the base is directed towards the impact site, as is the case for crater-hole fractures created in the skull by bullets [Fig. 11]). However, the "true" Messerer's wedge always has a sharp apex and concave lateral edges (Fig. 12), whereas "false" triangular bone fragments often have an irregular apex and convex lateral edges *(3,15)*. Within the triangular section of the tibia, bending fractures are more likely to be caused by a hit to the flat back surface than to the lateral or medial side, and particularly from the front *(16)*.

Messerer's fractures are becoming increasingly rare, which is likely the result of changes in the shape of the front of modern passenger cars (especially the elimination

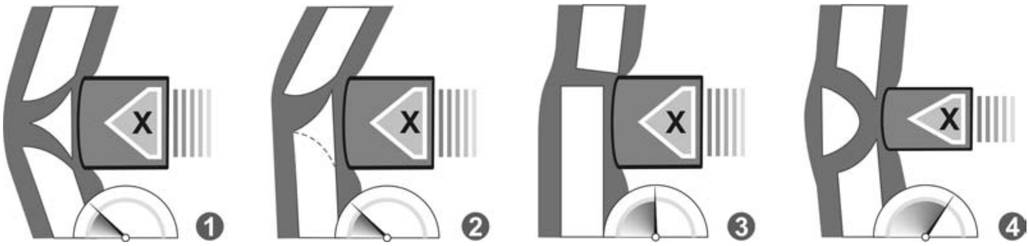

Fig. 11. Some patterns of long-bone diaphyseal fractures in pedestrian victims of traffic accidents: **(1)** "classic" bending fracture; **(2)** "incomplete" bone wedge; **(3)** "dynamic" transverse fracture with "phantom" wedges; and **(4)** "false" bone wedge.

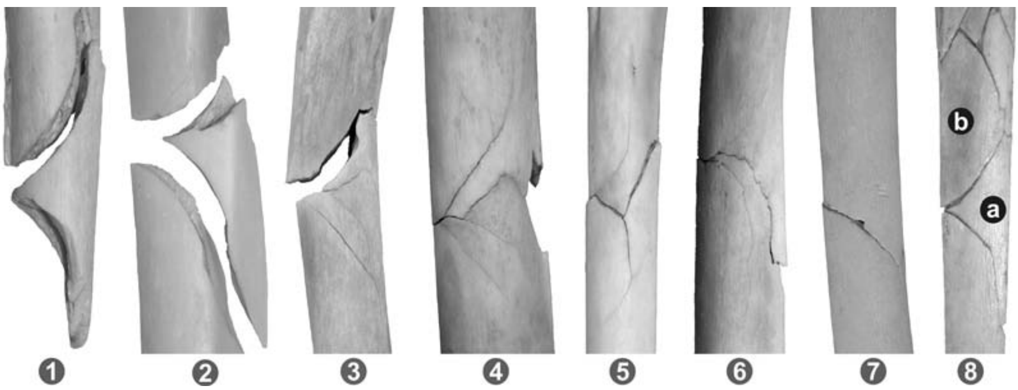

Fig. 12. Various patterns of "complete" **(1–2)** and "incomplete" **(3–7)** bending fractures. **(8)** "true" **(a)** and "false" **(b)** wedges. All impacts from right side of the figure.

of protruding bumpers) and the higher average speed on collision *(7,17)*. However, many apparently noncharacteristic oblique fractures are in fact "incomplete" bending fractures and the additional fissure of the fracture "supplementing" the wedge may be detected only on high-quality radiographs or after bone maceration (Fig. 12, part 3) *(16–18)*. Thus, if the oblique fracture fissure is clearly convex (i.e., it starts with a mild arch on one side of the bone and ends in a sharp angle on the opposite side), the direction of the external breaking force may be determined if one bears in mind that the edges of the Messerer's wedge must be convex in relation to its base (Fig. 12, parts 6 and 7) *(14,15)*. In many cases, after maceration of bones even the transverse fractures are found to be flexion fractures with so-called "phantom" wedges (Fig. 12, parts 4 and 5) *(17)*.

The spiral fractures (Fig. 13) are rare in victims of traffic accidents, because they are caused by torsional forces; e.g., from tangent hit of a pedestrian—i.e., sideswipes (author's personal observation). Being hit on the lateral body side of the body by the corner or side of a vehicle while walking along a road causes the body to rotate around the body mass-loaded lower limb *(4,5)*. A clockwise torsional load results in right-hand screw-like spiral fractures, whereas left-hand screw-like fractures are "counterclockwise" (looking up if the top of the bone is held and the bottom is twisted) *(18)*.

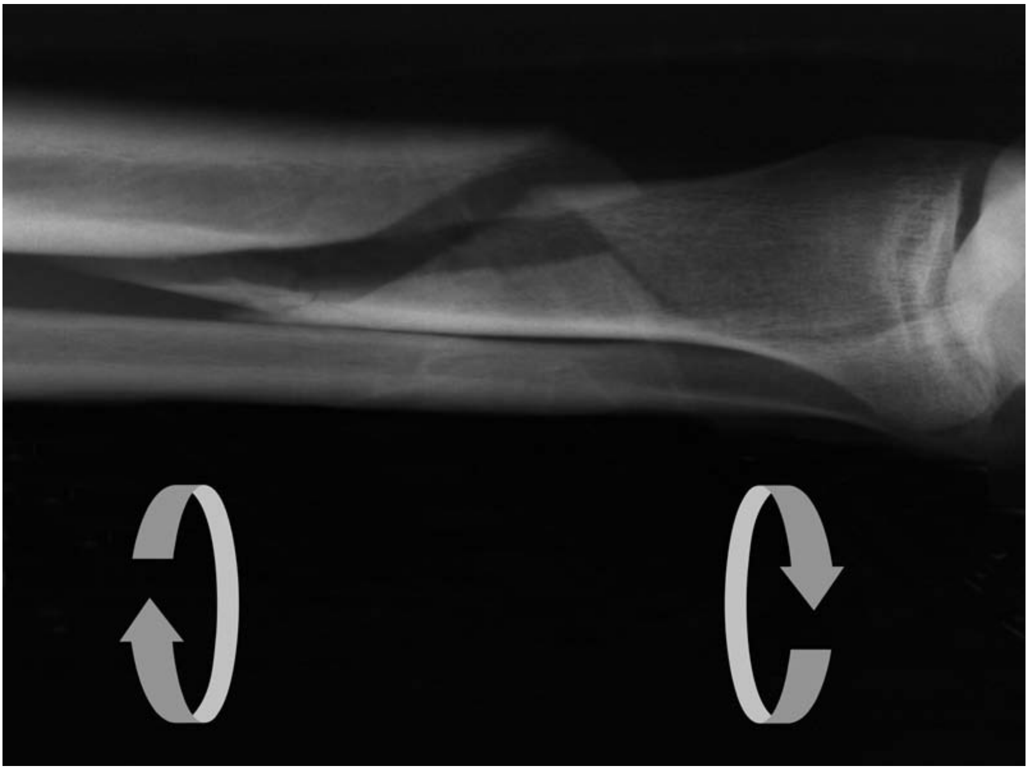

Fig. 13. Spiral fracture of tibial shaft.

In the case of axial loading (e.g., caused by dashboard injury to the femoral diaphysis area), the fracture fissures are often longitudinal (Fig. 14) *(19,20)*.

2.4. Knee Injuries

Mechanically, the knee joint is a modified hinge in which only flexion–extension and slight rotational movements are possible (the risk of injury is the highest when the knee is blocked in full extension). Unlike other joints, the shape of the joint surfaces does not ensure stability in the knee; instead, stability is provided by the menisci, as well as by ligaments and muscles. The lateral and medial walls of the joint capsule are strengthened by lateral collateral ligament (LCL) and medial collateral ligament (MCL). These ligaments are most tense in the extended knee, and they serve primarily to fix and stiffen the joint in this position and eliminate sideward movements. The knee joint has also two intraarticular ligaments—the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL)—whose course and attachments allow them to tighten in almost all joint positions. The ACL mostly counteracts anterior tibial dislocation and internal rotation, whereas the PCL counteracts posterior tibial dislocation and external rotation *(21)*.

Knee-joint injuries form patterns (Fig. 15) according to the direction of the external force and any pathological dislocation within the joint *(21–24)*. Thus, injuries occur during hyperextension (i.e., when the position of tibial and femoral diaphyses exceeds the

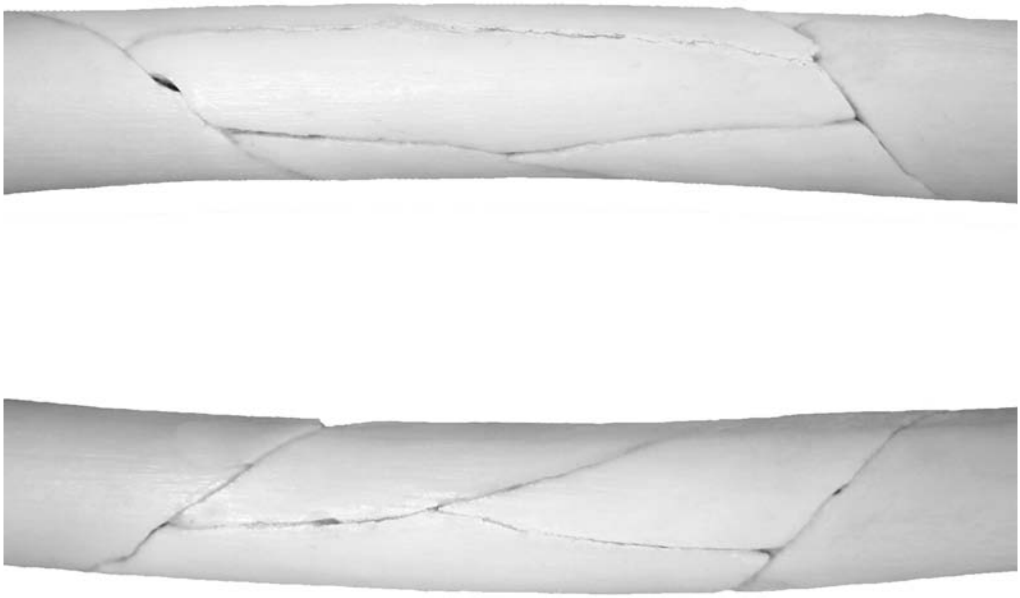

Fig. 14. Longitudinal fractures of femur shaft due to axial loading in dashboard-type injury.

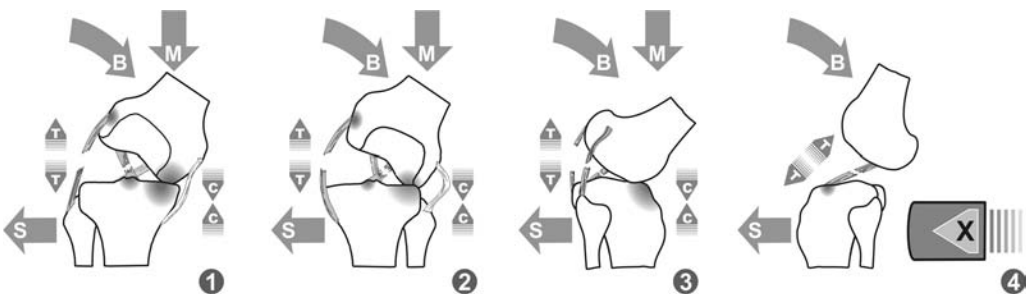

Fig. 15. The main mechanisms of knee joint injuries: **(1)** varus flexion; **(2)** valgus flexion; **(3)** hyperextension; **(4)** tibial translocation—bending force **(B)**, shearing force **(S)**, tearing force **(T)**, compression force **(C)**, limb load by body mass **(M)**, impact direction **(X)**.

normal range of physiological extension of the knee joint) and varus or valgus angulation (i.e., when the diaphyses bend in the frontal plane). Moreover, injuries to ligamentous structures may result from shearing forces (due to the dislocation of tibial and femoral diaphyses within the perpendicular plane). However, the isolated mechanism of dislocation is rare, because shearing force effects are masked by dominant bending injures. The only exceptions are isolated ACL injuries caused by hits from the rear that result in anterior dislocation of the proximal tibia relative to the femoral condyles (Fig. 15). The subsequent bending forces act in the natural range of articular movements ("pure" shearing effect) *(24,26)*.

Generally, the forces tearing the ligamentous structures act on one side of the joint while those crushing the bone act on the other side; the effects of these components are not always detectable simultaneously, however. In many cases, the only signs of ligamentous avulsion are the local bruises, which should be differentiated from the effects of direct

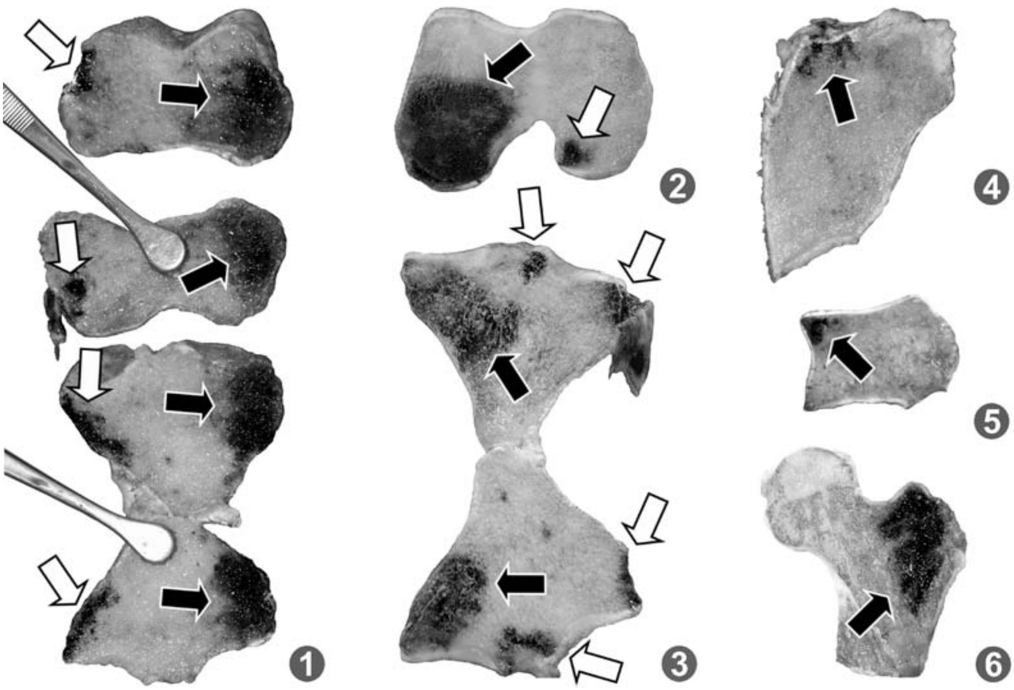

Fig. 16. **(1–3)** Bone bruises on tibial and femoral epiphysis frontal sections; **(4)** bruises at the anterior margin of tibial epiphysis sagittal section; **(5)** bruises on the trochlea tali section; **(6)** bruises on the femoral greater trochanter section (white arrows, ligament avulsion; black arrows, epiphysis compression).

trauma. To determine the mechanism of joint injury, it may be helpful to evaluate bone bruises; however, it is necessary to differentiate those caused by condylar compression from those resulting from tearing forces *(22–25)*. The former are usually extensive, located in the central and deep condyle structures, and reach under the articular surfaces of femoral and tibial condyles. They may be accompanied by macroscopically visible fissures of fractures or compression of bone trabeculae, occasionally with an indented or lowered condyle. On the other hand, the bone bruises resulting from avulsion (Fig. 16) are usually small and located peripherally within the lateral parts of the condyles (i.e., in the region of capsule attachments and collateral ligaments) or under the intercondylar prominence (in crucial ligament avulsions). They may be accompanied by small bone fragments tearing off at the site of ligamentous attachments. In living persons, bone bruises can be detected by magnetic resonance imaging (Fig. 17) *(22,23,25)*.

The characteristics of meniscus injuries (Fig. 18) vs fibular head fractures (Fig. 19) may be useful for differentiating the mechanisms of knee joint fractures.

2.5. Ankle Injuries

The upper portion of the ankle joint is a hinge articulation. Physiologically it allows only dorsal and plantar flexion around the axis running through the center of the trochlea tali. The compactness of this joint is ensured by the ligaments attached to the

Fig. 17. Magnetic resonance images of a bruise in the lateral femoral condyle (image courtesy of Marzena Janczarek, MD, from the Department of Interventional Radiology and Neuroradiology, Medical University of Lublin, Poland.

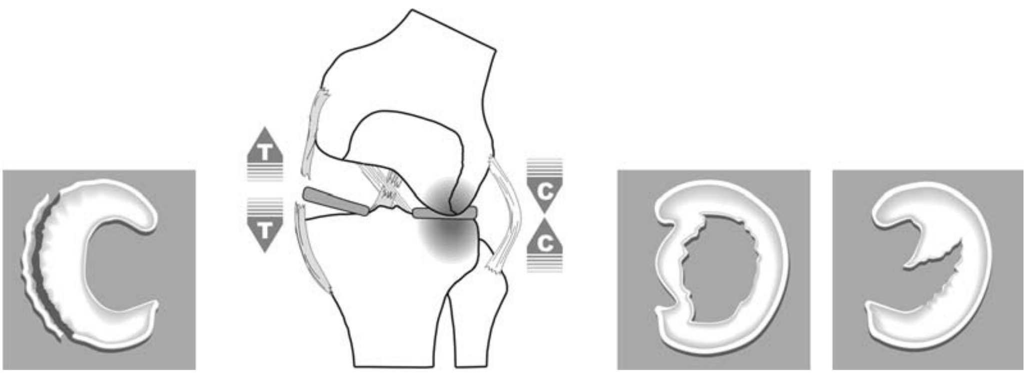

Fig. 18. The mechanism of meniscus injuries in valgus flexion of the knee: marginal separation (left) and "bucket handle" or "parrot beak" tears (right).

lateral and medial malleolus, while anteriorly and posteriorly the joint capsule is strengthened only by muscle tendons.

Similar to injuries to the knee joints, ankle injuries form patterns (Fig. 20) determined by the direction of the external force and dislocation of joint structures *(26–28)*. Thus, injuries occur when the distal tibial epiphysis lies beyond the range of physiological flexion (dorsal or plantar) and when excessive pronation or supination of the shins towards the fixed foot is observed (Table 2). Contrary to typical ankle sprains caused by improper positioning of the foot during running, jumping, or skidding, victims of traffic accidents often lack the rotational component and their injuries are caused by forces acting in one direction only. Injuries that occur during the first phase of trauma are usually caused by tearing forces, while those occurring during later phases of trauma are usually caused by crushing 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

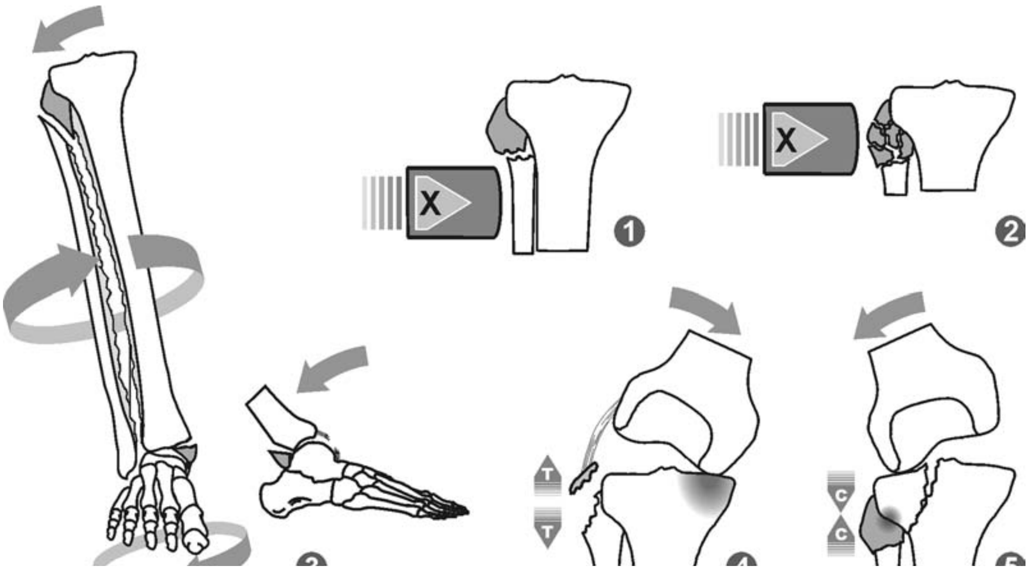

Fig. 19. Mechanisms of fibular head fractures: **(1,2)** direct injury; **(3)** pronation-rotation; Maisonneuve's fracture; **(4)** avulsion caused by varus flexion; **(5)** compression caused by valgus flexion.

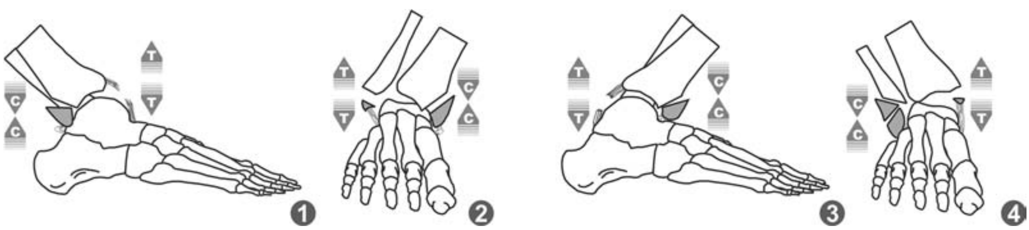

Fig. 20. The main direction of pathological dislocation of bone structures within the ankle joint in victims of traffic accidents: **(1)** plantar flexion; **(2)** supination; **(3)** dorsal flexion; **(4)** pronation.

edges press the lateral (pronation) or medial (supination) malleolus (Fig. 16, part 5). Avulsion of the collateral ligaments may disrupt the ligament or cause separation of the malleolus (*see also* Table 2). Because there are no ligaments strengthening the front and back of the joint capsule, avulsion of anterior or posterior edges of the distal epiphysis of the tibia is not observed (in fact, edge fractures are always caused by the compression mechanism).

2.6. Femoral Proximal Epiphysis Injuries

In injuries to the lateral side of the greater trochanter (Fig. 16, part 6), the victim may sustain bone bruises within the trochanter (Fig. 21) or more rarely in the femoral head and central fractures of the hip joint (or central dislocations when the femoral head is translocated into the interior of the pelvis) *(7,26)*. In car occupants central fractures or injuries to the posterior margin of the acetabulum may result from forces travelling along

Table 2
Mechanisms of Ankle-Joint Injuries in the Victims of Traffic Accidents

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

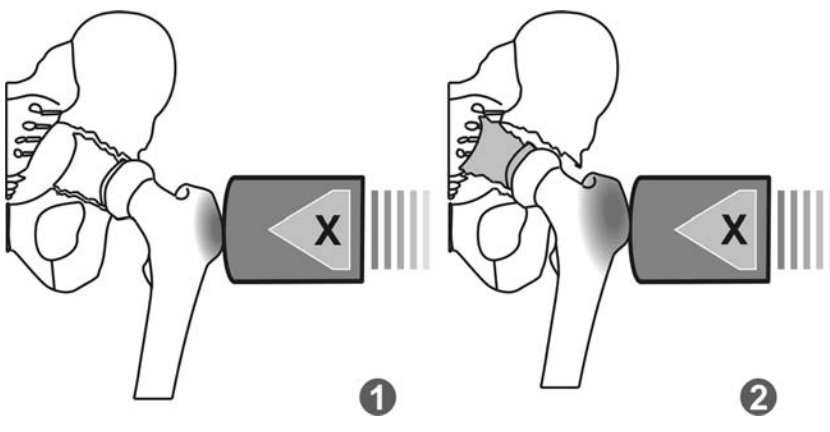

Fig. 21. The mechanism of bone-bruise onset in the great trochanter and central fracture (dislocation) of the hip joint (X, impact direction).

the axis of the femoral diaphysis (dashboard injuries), as well as during high-energy trauma while the thighs are in substantial adduction (e.g. when the passenger's legs are crossed) or abduction (e.g., when the passenger's thighs are kept apart). Under such circumstances, the femoral head may move outside the acetabulum (Fig. 22) *(3)*.

2.7. Mechanisms of Ankle and Knee Joint Injuries in Traffic Accidents

2.7.1. Car-to-Pedestrian Accidents

For many years, the efforts of researchers and car companies have been focused on reducing the degree of trauma in traffic-accident victims *(11,29)*. Changes in bumper

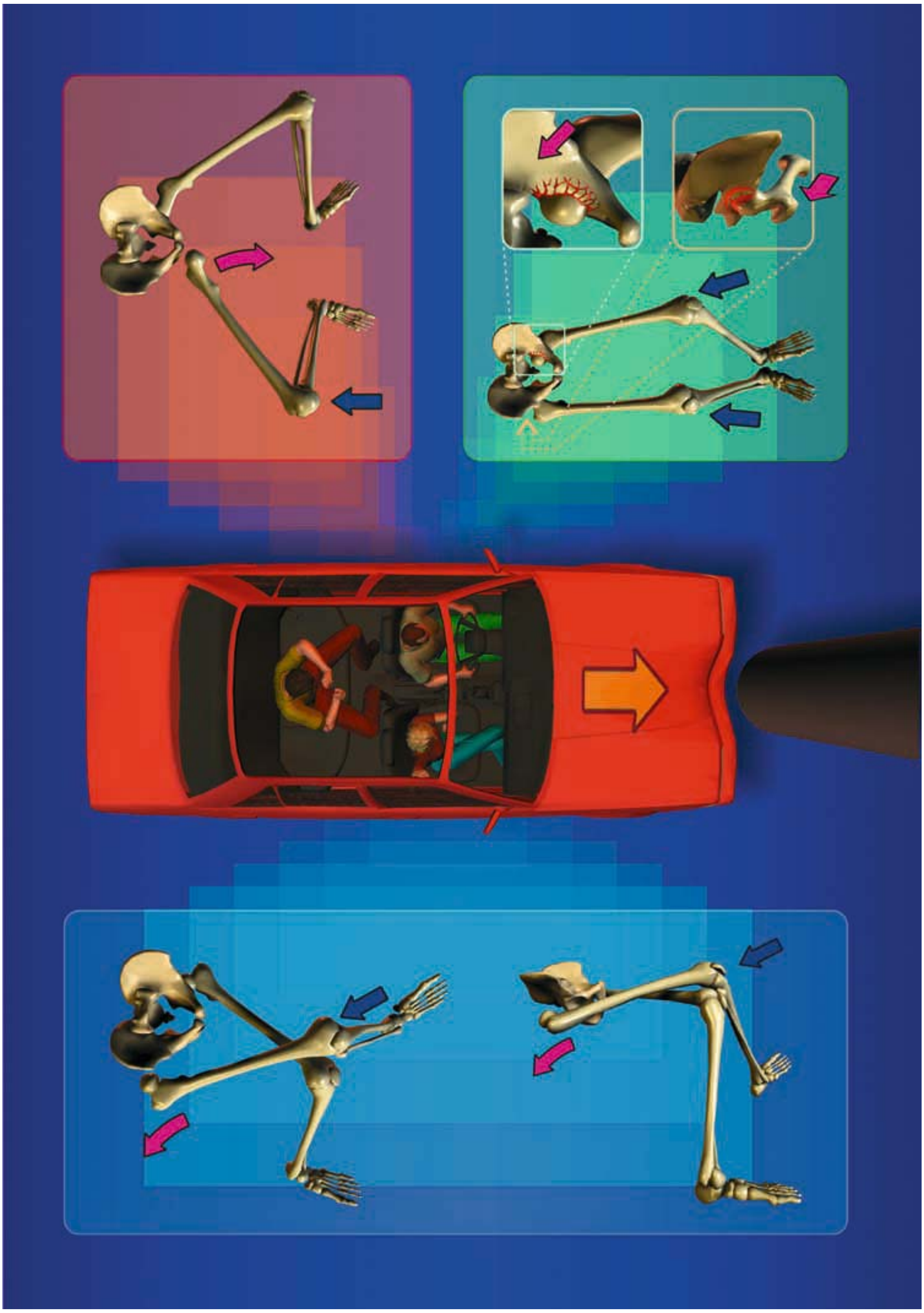

Fig. 22. The pattern of hip dislocation in a frontal collision depends on the initial sitting position of vehicle occupants. *See* **Color Plate III**, following page 240.

construction and the distribution of energy on impact over a larger surface have decreased the number of lower-extremity fractures in pedestrians hit by cars. Unfortunately, the redistribution of impact energy paradoxically has increased the risk of injury to joint structures, and ligament injuries have resulted in disability more often than even multisite diaphyseal fractures. By contrast, the low, protruding, and inflexible bumpers in older vehicles frequently caused fractures in the shins; this prevented the knee joint from absorbing the impact energy and, thus, protected it from the effects of trauma. In terms of forensics, however, the changes made in modern vehicles have increased the ability of investigators to reconstruct the accident based on the mechanism of trauma *(7,24)*.

The presence of ankle- or knee-joint injuries indicates that the pedestrian was hit while in an erect position, *(27)* as such injuries—especially those caused by the compression mechanism and resulting in bone bruises in the central parts of tibial and femoral condyles—occur only when the limb is loaded by body mass. When the victim is run over while in the recumbent position, the injuries are noncharacteristic and usually occur only when the wheel rolls directly over the ankle or knee. Running over of the pedestrian may cause external dislocations of the femoral head outside the acetabulum; such hip-related injuries are not normally observed in victims who were standing erect when hit *(7)*.

When a standing pedestrian is hit by a passenger car, protruding elements of the car hit much lower than the victim's center of gravity, causing the victim's upper body to rotate in the direction opposite that of the speed vector of the car. One or both ankles (depending on whether the victim was standing still or walking when hit) may twist along the rotation axis, causing the body to spread over the hood, in which case the thigh and hip regions are hit first, followed by the trunk and head *(4)*. In this hits caused by small- or medium-sized passenger cars of a trapezoidal or pontoon body, the site of primary impact is usually located in the middle or proximal part of the shins (medium-height victims). Large passenger cars and delivery vans hit at the level of the knee, and trucks with a high bumper may hit the proximal thigh or hip girdle (such a "high" impact is likely to knock the pedestrian down, which increases the risk of a secondary runover). During the first phase of the accident, the victim's body "adjusts" to the shape of the front of the vehicle, and the place of force application determines the type of pathological dislocation that will occur in the joint structures and consequently the mechanism of ankle and knee-joint injuries. On the other hand, injuries to proximal femoral epiphyses (the greater trochanter area) are good markers of an ipsilateral hit while the victim was in the erect position, no matter what the shape of body of the car *(7,26)*.

In contrast to passenger cars, trucks with a high bumper location often cause a reversed complex of injuries in both the knee and ankle joints (the lever principle; compare Fig. 23 and Table 3). Delivery vans, light trucks, sport utility vehicles, pickups, and large passenger cars usually cause a reversed complex of injuries in ankle joints only. Very low hits at the level of distal shin parts resulting in reversed injury complexes in the knee are rare (e.g., they are seen in tall victims and with intensive braking of the vehicles before the accident; particularly those vehicles with low floor and a wedge-shaped body). In short victims, the passenger-car hits resemble the delivery-van hits whereas in children they resemble the truck hits *(7,24,26,27)*.

Therefore, the mechanism of knee-joint injuries should always be considered within the context of every circumstance of the accident and the shape of car body.

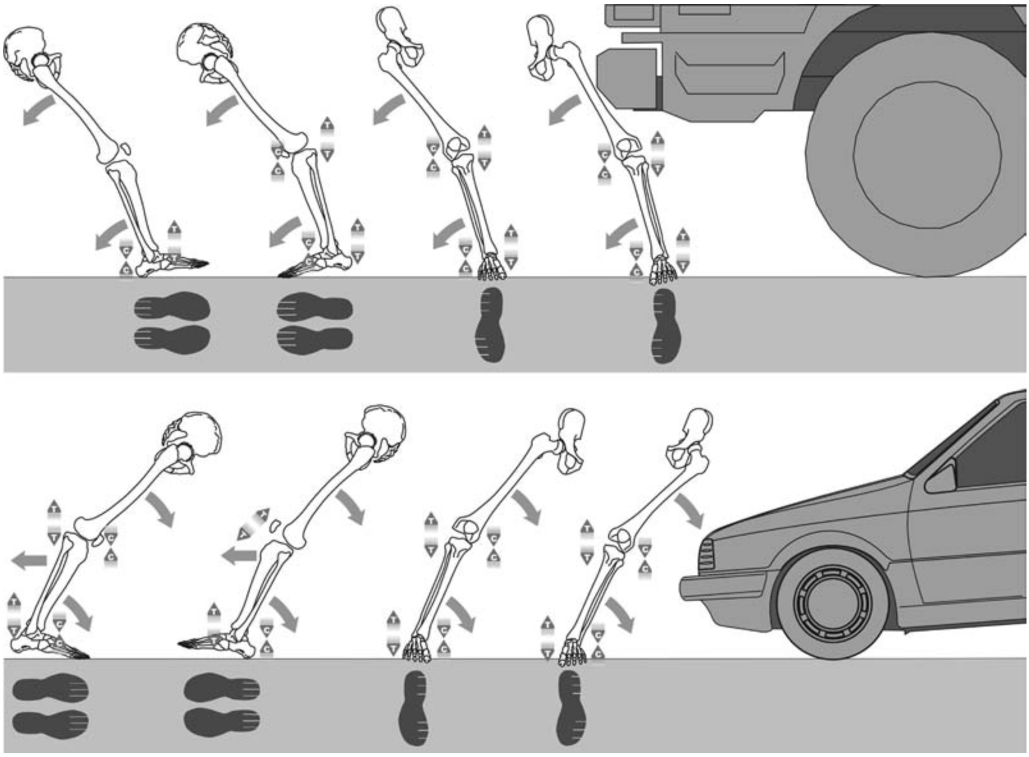

Fig. 23. The most common mechanisms of ankle and knee-joint injuries and the mechanisms of shoe–sole scratches in pedestrian hits caused by small passenger cars and trucks with a high bumper location. Compression forces (C); tension forces (T).

Table 3
The Most Common Mechanisms of Ankle- and Knee-Joint Injury in Pedestrians Hit by Vehicles With Various Vehicular Body Shapes

Joint	Vehicle Type	Impact Height	Mechanisms of Injury According to Hit Direction			
			Anterior	Posterior	Lateral	Medial
Ankle	Passenger	shin	dorsal flexion	plantar flexion	pronation	supination
	Van**	knee	plantar flexion	dorsal flexion	supination	pronation
	Truck	thigh	plantar flexion	dorsal flexion	supination	pronation
Knee	Passenger	shin	hyperextension	translocation*	valgus flexion	varus flexion
	Van**	knee	hyperextension	–	valgus flexion	varus flexion
	Truck	thigh	–	hyperextension	varus flexion	valgus flexion

*isolated injury to the ACL due to anterior translocation of the proximal tibial epiphysis in relation to the femoral condyles.

**also sport utility vehicles, pickups, or large passenger cars (non breaking).

ACL, anterior cruciate ligament.

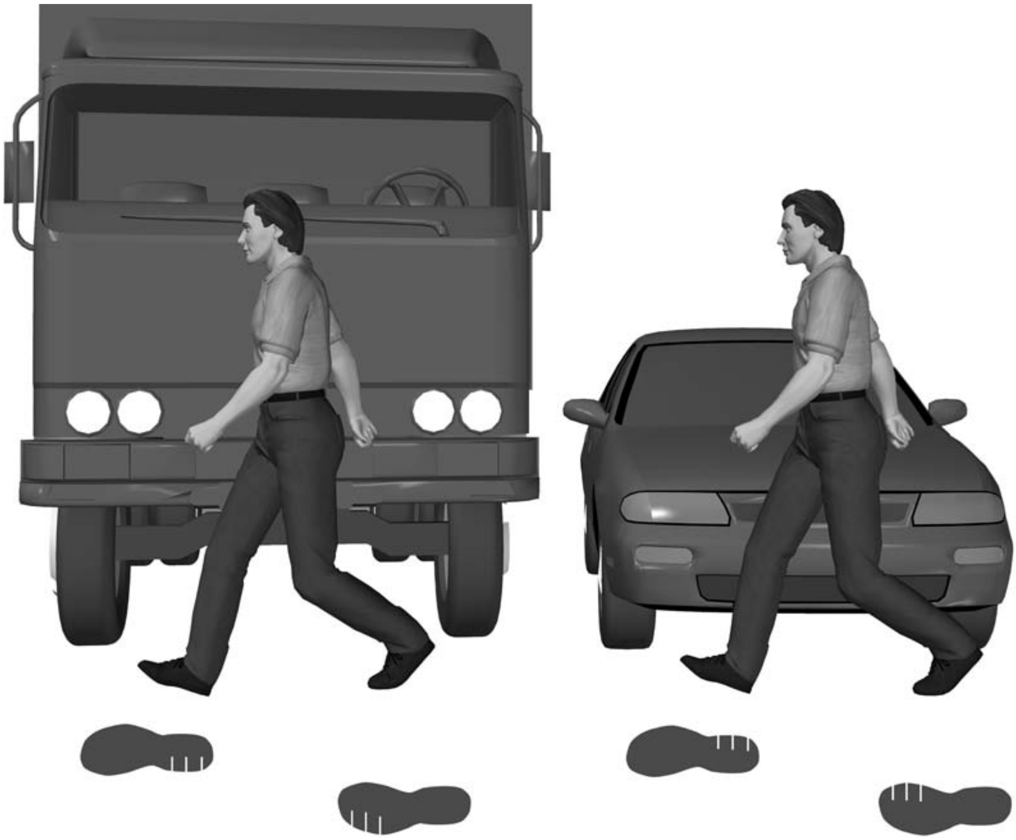

Fig. 24. The shoe-sole scratches indicate the impact direction and walking phase of the pedestrian.

However, when the impact direction is explicitly defined (e.g., on the basis of soft-tissue injuries), the findings in knee- and ankle-joint injuries may be used to determine the type of vehicle that was involved, particularly in hit-and-run accidents.

The mechanism of ankle-joint injury often correlates with scratches on the soles of the shoes *(28)* near the edge of the shoe. When a small passenger car is involved, these scratches are usually found on the side ipsilateral to the side of the vehicle that made contact with the body; when a truck with a high bumper is involved, they are usually found on the side of the shoe that is contralateral to the side of the body that was struck. In some cases, the location of these scratches can be used to determine the walking phase during which the individual was struck (Fig. 24).

In oblique pedestrian hits, mixed injury complexes are likely to occur in the region of ankle and knee joints, e.g., during dorsal flexion with the pronation component and during hyperextension with the valgus-flexion component in passenger-car anterolateral hits *(24,27)*. In corner hits (Fig. 25) or sideswipes, rotation may occur within the ankle joint, e.g., a corner of the car may rub against the lateral side of a pedestrian walking along the road, resulting in a pronation–rotation trimalleolar fracture (Fig. 19, part 3).

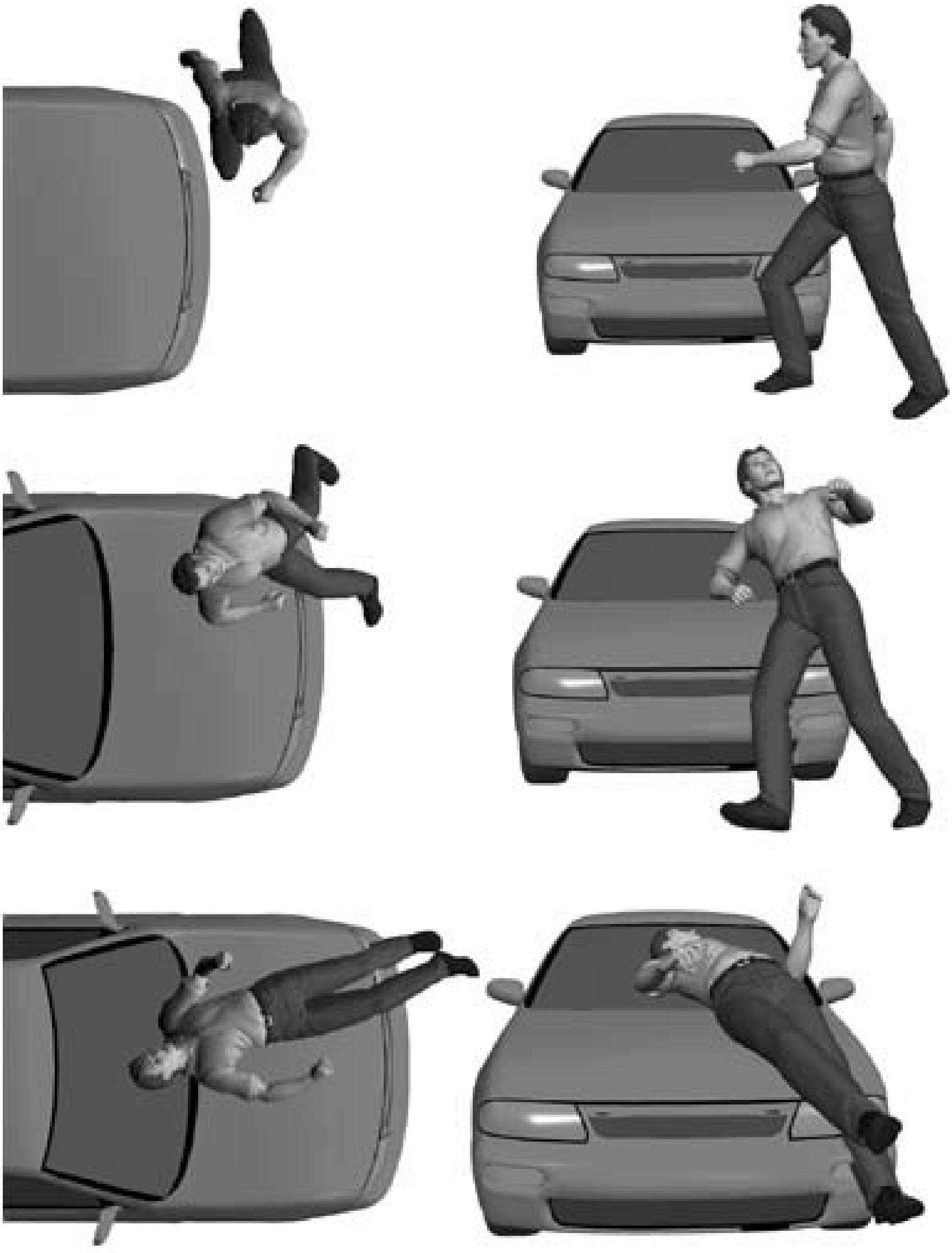

Fig. 25. Rotation of the victim's body in a car-to-pedestrian hit.

2.7.2. Car-to-Bicycle Accidents

Ankle- and knee-joint injuries are only slightly less common in cyclists than in pedestrians. This indicates that the pressure exerted on the bicycle pedals by the legs plays a role similar to that of body mass loading in the extremities in pedestrians.

In passenger-car-cyclist hits, the mechanisms involved in ankle-joint injuries (in back and lateral hits) are the same as those in similar pedestrian groups. Injuries to the knee joint are identical to those in pedestrians in lateral hits, only; in front and back hits, passenger cars cause primarily "reversed" injury complexes (Fig. 26). For example, hyperextension of the knee is a typical marker of a back hit in cyclists. Passenger cars usually do not cause knee joint injuries in front hits of cyclists, while almost all such hits cause hyperextension-related injuries in pedestrians (similar to cyclists hit in the front by a truck) *(26)*.

The relations described above may be used to distinguish the means by which a cyclist was hit vs a pedestrian walking with a bike. Bruises in the subcutaneous tissue beneath the medial aspects of the proximal femur (and the scrotal sac in men; Fig. 27) may be used for this purpose, since they are more common in cyclists (due to contact with the saddle) than in pedestrians *(26)*. In oblique passenger car-to-bicycle hits (usually at an angle of <30°) the cyclist's thighs and buttocks rotate the saddle in the direction opposite to the site of impact (Fig. 28), whereas in a perpendicular hit, the saddle rotates towards the striking vehicle (Fig. 29) *(30)*.

2.7.3. Inside-Car Casualties

Injuries to ankle joints and foot bones are common in car occupants and develop most often during front hits primarily as a result of floor intrusion (equally common in drivers and passengers), contact with pedals, and the foot becoming trapped under pedals (in drivers only, and more frequently in the right than in the left leg). The imprints of control pedals on the soles of shoes may be used to determine the circumstances responsible for injuries and to identify the driver. The mechanism of ankle-joint injuries consists of axial loading with simultaneous rapid dorsal flexion, supination, or pronation of the foot *(31)*.

Knee-joint injuries result from contact between the legs and the dashboard. Any of four different mechanisms may be involved (Fig. 30), based on the shape of the passenger compartment, the position of the passenger's seat, and the passenger's height, as well as whether the victim was belted or the occupant's compartment was compressed *(32)*. The determination of the site of contact between the legs and elements of the car's interior makes it easier to find trouser cloth that has rubbed off or melted into plastic dashboard elements. If the occupant's chamber was not compressed and the control panel was not translocated, the presence of dashboard injuries indicates that the victim was not belted on collision.

The most common contact is made between the front surface of a bent knee and the dashboard. This is likely to cause fractures between the patella and acetabulum (Fig. 30, part 1a–f, Fig. 31).

Such injuries are equally common in drivers and car occupants, and the nature of hip injuries may also indicate the position of the victim in his or her seat (compare Subheading 2.6 and Fig. 22).

In nonbelted occupants, the knee is more likely to be hyperextended (Fig. 30, part 4) in the front seat passenger when he is thrown from the car through the windscreen. On

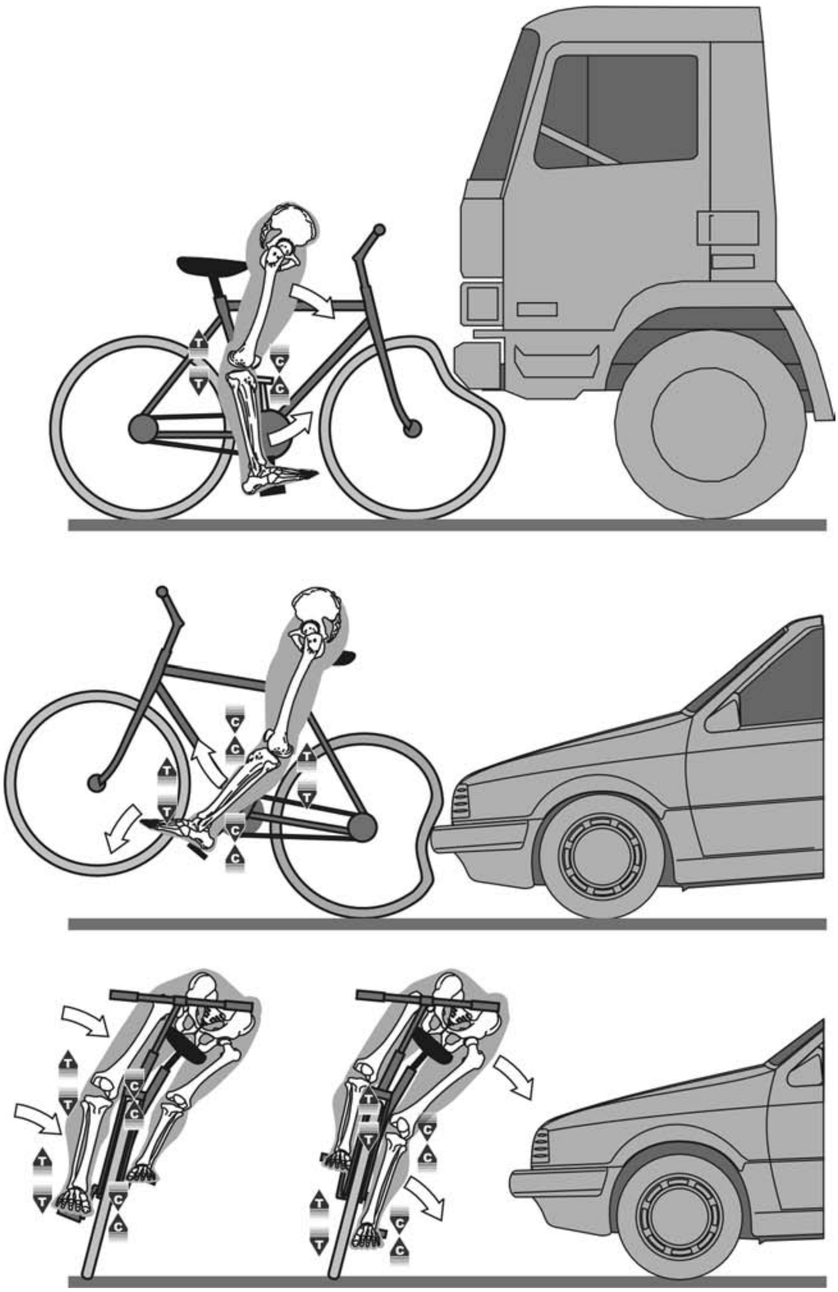

Fig. 26. The most common mechanisms of ankle and knee joint injuries in cyclists hit by passenger cars and a truck with a high bumper location.

the other hand, drivers are likely to experience splitting-compression fractures of the tibial plateau as a result of pressure on the femoral condyles when a leg is trapped between the floor and instrument panel (Fig. 30, part 3).

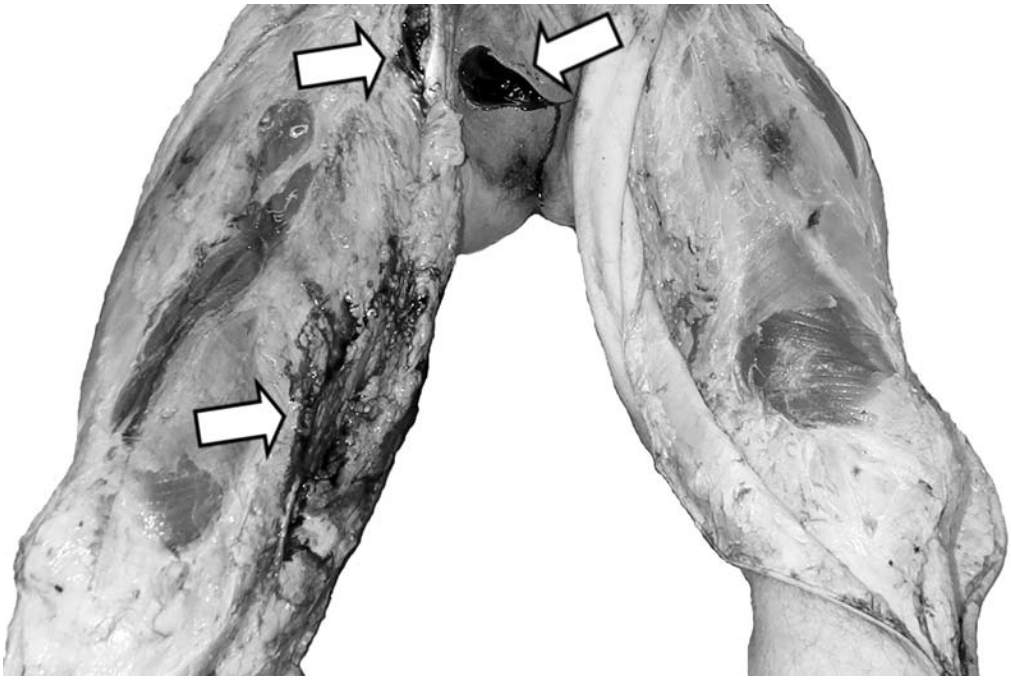

Fig. 27. Bruises in the perineum, scrotal sac (incised), and subcutaneous tissue of the medial surface of the right thigh and right groin in the cyclist caused by contact with the saddle.

Fig. 28. The direction of rotation of the saddle in car-to-bicycle collisions in the left oblique hit **(1)** and left perpendicular hit **(2)**.

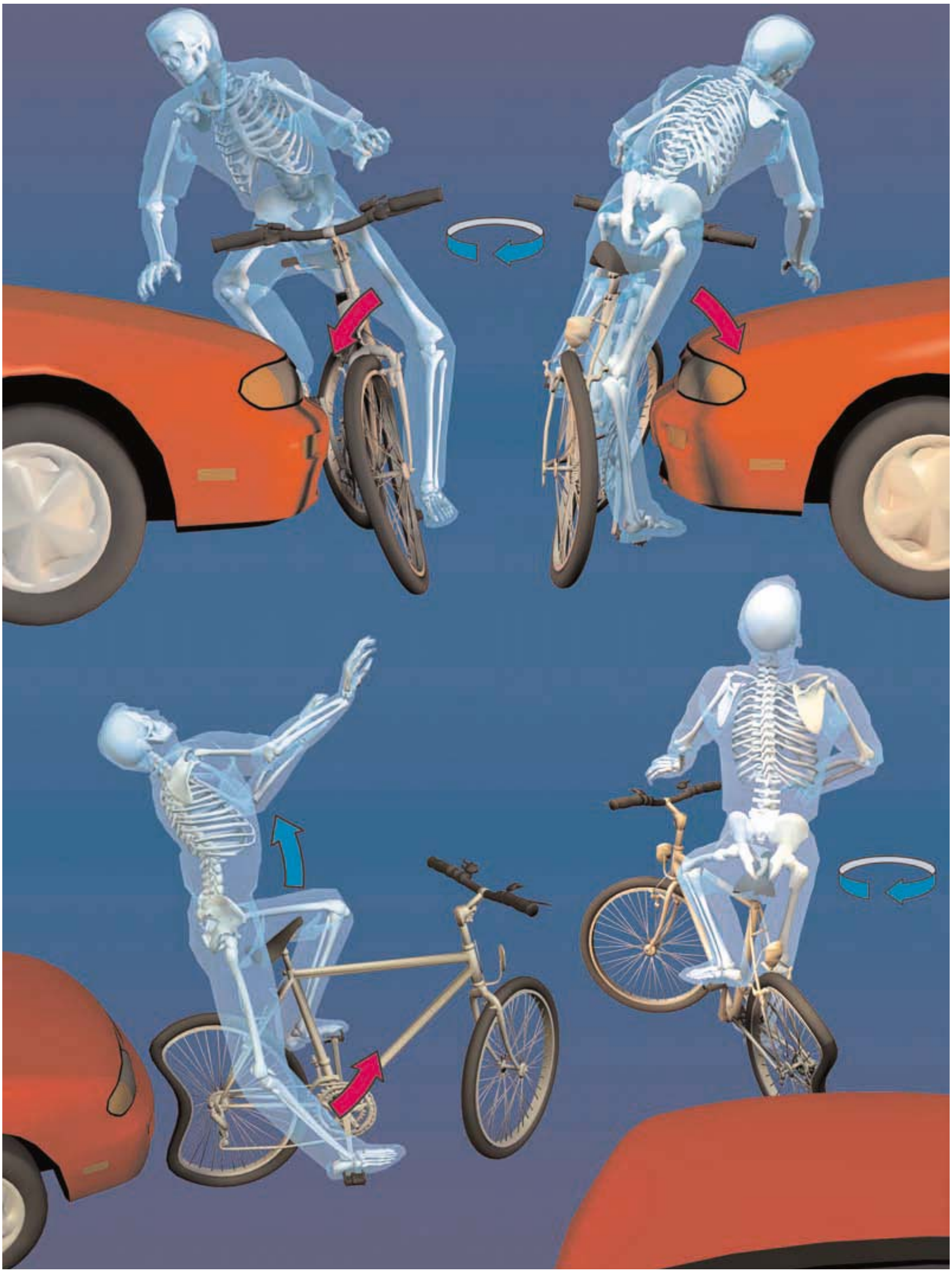

Fig. 29. The direction of knee joint dislocation and rotation of the saddle in car–bicycle collisions in relation to the direction of the impact. *See* **Color Plate IV**, following page 240.

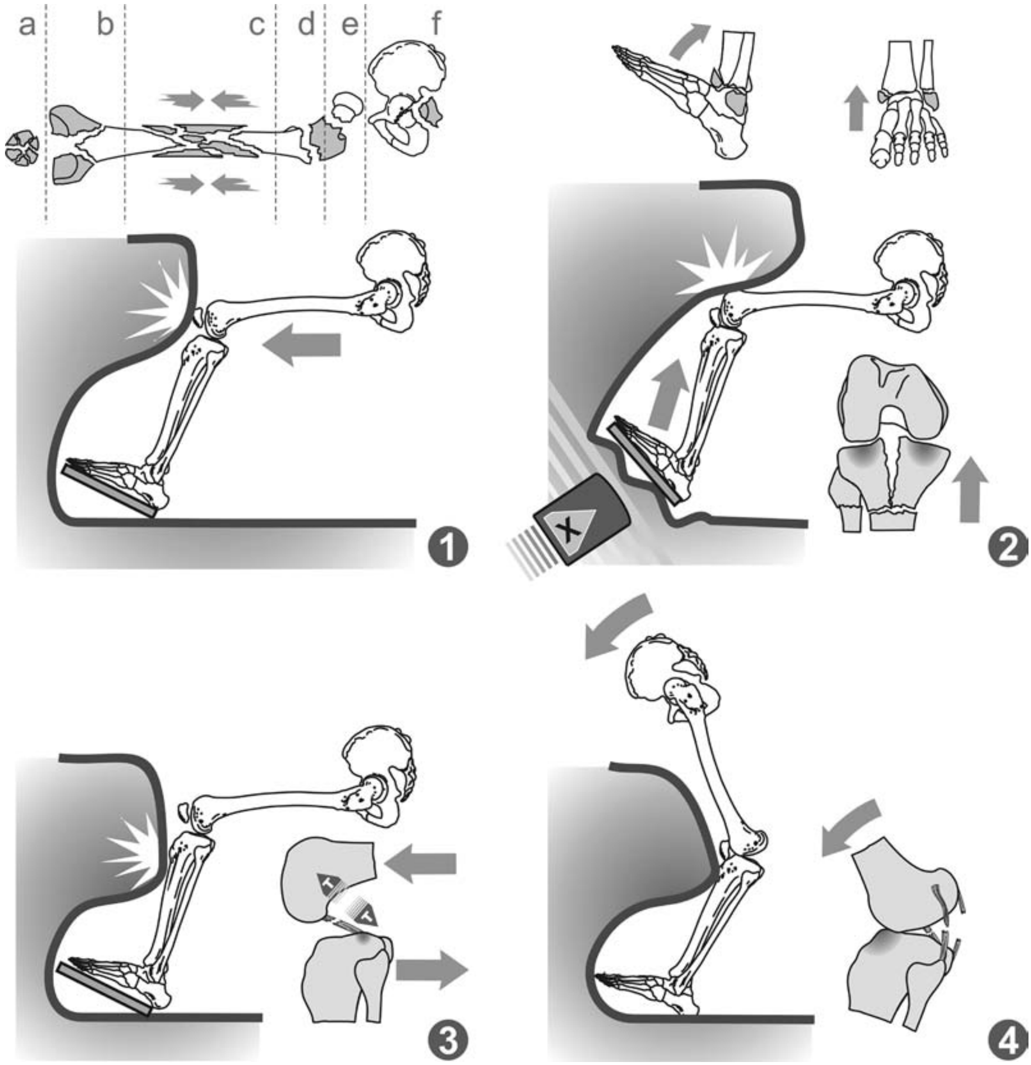

Fig. 30. Patterns of dashboard injuries in front collisions in nonbelted occupants.

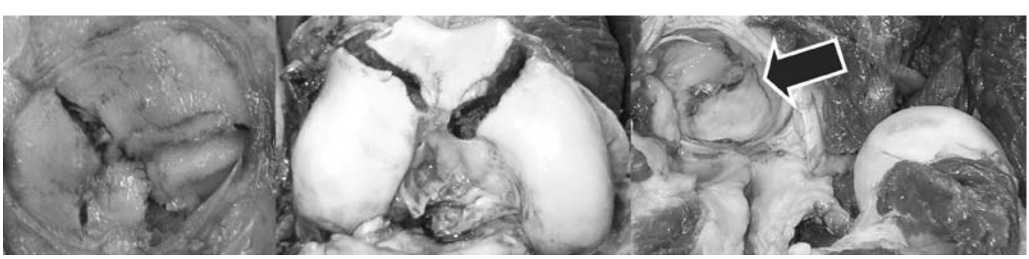

Fig. 31. The dashboard injury complex: "watch-glass-break"-type fracture of patella, femoral condyles splitting fracture, and acetabulum fracture.

2.7.4. Motorcycle Accidents

From the perspective of a forensic expert, the major difficulty in evaluating motorcycle accidents is to identify the motorcycle driver and passenger rather than to determine the impact direction (which is usually explicitly shown by the motorcycle damage).

The lateral car-to-motorcycle hits are similar to car-to-bicycle hits and may result in similar injuries to joint structures of the lower limbs (both in drivers and passengers). In frontal hits (both in high and low obstacles), the situation of motorcyclists is similar to that of car drivers and the motorcycle passenger is "protected" by the driver's body sustaining no serious lower limb injuries (moving along the driver's back, the passenger is thrown off the motorcycle and sustains some secondary injuries after hitting the road). The driver moving to the front due to inertia often hits the motorcycle elements with his knees sustaining injuries similar to the "dashboard" injuries in car occupants (also similar to the perineum injuries in cyclists). Moreover, the motorcycle driver is more bound than the bicycle rider to his vehicle and frequently sustains lower limb injuries when pressed by the motorcycle after collapsing or rubbing against the road surface *(33)*.

3. *Trials Estimating the Speed of Vehicle at the Moment of Collision*

So far attempts to determine the crash speed on the basis of the severity of injuries have brought no reliable (sufficiently precise and repeatable) methods of crash-speed determination *(5)*. The commonly used methods of injury scaling (AIS, ISS, CRIS) are useful only for statistical studies as they show a high level of error between the estimated extent of injury and the real collision speed in particular cases.

Studies *(8,29,34,35)* of car-to-pedestrian accidents have led only to some general conclusions (beside the obvious one, that the fracture frequency increases with the collision speed), e.g., the greater the lower limb body-mass load and the older the victim, the greater the risk of lower limb fractures. According to Spitz *(9)*, bumper fractures may occur at collision speeds above 20 km/h (14 mph) and the multi-fragment fractures as a rule are observed above 40 km/h (25 mph). At speeds higher than 90–100 km/h (60 mph) inguinal skin ruptures (Fig. 32) usually are present (they never occur below 50 km/h = 30 mph) and the limbs often get amputated (Fig. 33) as the limb is pulled under the front bumper of the car and disrupted due to the pulling by the upper body part thrown over the car-front (the disrupted distal limb may still be held by the skin or clothes and be completely severed during the "somersault" over the car—sometimes the limb is found very far from the hit site).

The injuries to knee and ankle joints are almost useless in estimating the collision speed, as they are caused by indirect bending mechanisms and occur even at low collision speeds. The ankle fractures result from the body-mass loaded shin–fixed foot translocation and often are found in accidental falls unrelated to traffic incidents. The main cause of knee joint injuries, however, is the pressure exerted by femoral and tibial joint structures, while the car is responsible only for pathological dislocation of these structures.

Thus, the determination of collision speed on the basis of the character of injuries can be only approximate, and the opinions should be left to traffic experts and their technical criteria (e.g., tire marks, throw distance, the area of glass scattering, wrap around distance).

Fig. 32. Inguinal skin rupture.

Fig. 33. Lower limb amputation in the pedestrian victim.

4. Examples of Reconstruction

4.1. Sample Case 1

An 81-yr-old pedestrian was hit by the front of a delivery van. The driver and passenger of Ford claimed that the pedestrian had run under the car from the right pavement. Although there were no other witnesses, it was determined that the pedestrian

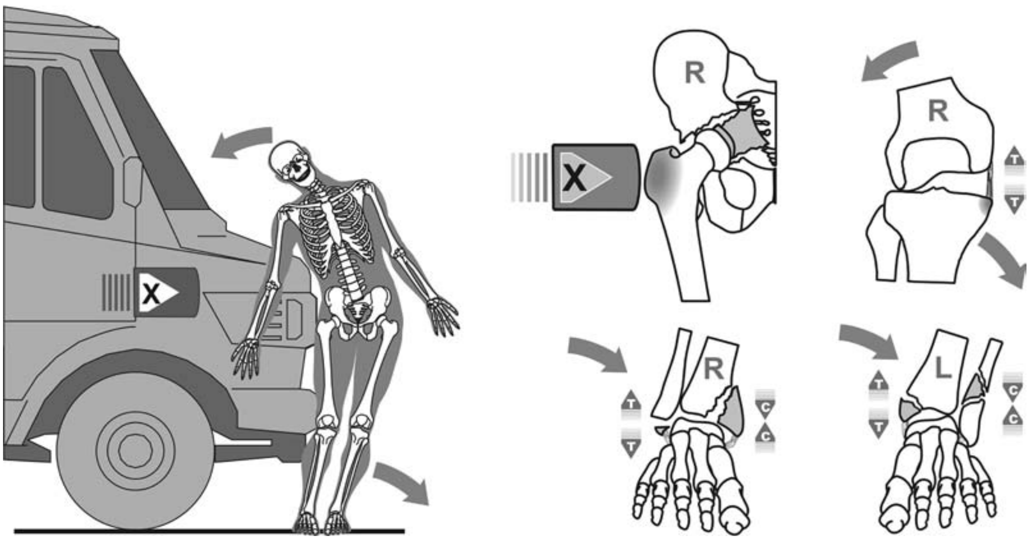

Fig. 34. The mechanism of ankle, knee, and right hip joint injuries in case 1.

had left home to go to church located on the right side of the road (looking from the driver's position, he would have crossed the road from the left to the right side). The autopsy revealed several injuries that support this (Fig. 34):

- damage to the lower attachment of the medial part of joint capsule due to valgus flexion of the right knee joint,
- a bimalleolar fracture of the right ankle due to the supination mechanism,
- a bimalleolar fracture of the left ankle due to the pronation mechanism,
- a central fracture of the right hip joint and bruises on the right greater trochanter section,
- injuries to the soft tissues and organs mainly located on the right body side and contralateral avulsion of the cervical spine ligaments.

4.2. Sample Case 2

A 20-yr-old injured man was found at the end of bloody marks indicating his having been dragged along the road for 1365 m. Without regaining consciousness, he died of brain injuries within 24 h. The next day a vehicle was found with a broken lower edge of the front plastic material under the front bumper and with some traces of victim's tissues and torn clothes on the chassis.

Beside the characteristic injuries of dragging along the rough surface (extensive epithelial excoriations and oval head wound with abraded external lamina of the right parietal bone), the autopsy revealed the injuries typical of an earlier front hit in the erect position: subcutaneous bruises in front surfaces of both shins with noncharacteristic fractures of both bones of the right shin, injuries to both knee joints characteristic of the hyperextension mechanism (disruption of the posterior part of the joint capsule with attachment bruises of both collateral ligaments; and on the right side, the patella fracture, disruption of both crucial ligaments and massive bone bruises within the region of the anterior tibial edge), and injuries to the right ankle joint characteristic of the dorsal flexion mechanism (crushing of the anterior edge of the distal tibial epiphysis).

Those findings demonstrated that the earlier hit was caused by another vehicle because the car had no signs of any repairs. This hypothesis was confirmed by fiber examinations of the victim's clothes that revealed microtraces of glass particles and paint belonging to another car.

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