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Motorbike protective helmets, construction, testing and its influence on the type and severity of injuries of motorbike accident casualties: a literature review

Maciej OBST[1,2], Szymon RZEPCZYK[3], Sebastian GŁOWIŃSKI[4,5], Czesław ŻABA[3]

[1] BTU Cottbus-Senftenberg, Chair of Engineering mechanics and machine dynamics, Universitätsplatz 1, 01968 Senftenberg, Germany
[2] Institute of Applied Mechanics, Poznan University of Technology, ul. Jana Pawła II 24, 60-965 Poznań, Poland
[3] Department of Forensic Medicine, Poznan University of Medical Sciences, ul. Święcickiego 6, 60-781 Poznań, Poland
[4] Institute of Physical Culture and Health, State Higher School of Vocational Education in Koszalin, Lesna 1, 75-582 Koszalin, Poland
[5] Institute of Health Sciences, Slupsk Pomeranian Academy, Westerplatte 64, 76-200 Slupsk, Poland

Corresponding author: Maciej OBST, email: maciej.obst@put.poznan.pl

Abstract A motorcycle or moped helmet is currently mandatory, and provides basic protection to the user of a motor-powered two-wheeler against the possible consequences of a road accident. A wide market offer of various protective helmets allows one to choose from many different design solutions used by the manufacturers. The introduction of a protective motorcycle helmet is associated with the need of meeting the conditions set out in legal regulations. In recent years there have been changes in the legal provisions regarding to protective helmets and the conditions imposed on helmets are becoming more and more restrictive. There have also been changes in the conditions for conducting the helmet approval tests. Regulations valid in Europe include the Economic Commission of Europe (ECE), whereas regulations in the United States are created by the Department of Transportation (DOT). Despite the advanced construction of protective helmets, various test methods, and changes in legal regulations, the problem of the effective protection of the heads of two-wheeler users remains valid. The article presents an actual state of constructions for motorbike helmets, safety level, testing methodology and actually applicable law regulations. This analysis includes a wide medical description of motorcyclist injuries and helmet obstacle impact behaviour. Further studies are required to estimate the head and neck injuries caused by accidents involving motorcycles and other materials. Therefore, construction and testing methods should be developed accordingly. This review presents the current state of knowledge that can be used as the basis for helmet tests and medical assessments of body injuries.

Keywords: motorbike helmets, head injuries, neck injuries, helmets safe.

1. Introduction

Road accidents are still a problem which is hard to be solved now and probably soon be also actual. At the same time, traffic accidents are the leading cause of injuries in the community [1]. Despite advances in technology, newer helmet designs, motorcyclists' wear, protective systems and improvements to road infrastructure, the problem of injuries among motorcyclists remains an issue that requires ongoing scientific study. Sosin et al. compiled information related to head injuries and deaths as a result of motorcycle accidents [2]. Authors observed that in the United States motorcyclists aged 15 – 34 accounted for 69% of the fatalities in accidents in the years 1979 – 1984, where 53% of the 28744 deaths resulted from head injuries. Additionally, a drastic increase in mortality occurred among motorcycle riders who did not use motorcycle helmet head protection. In Great Britain between 1995 and 2004, the fatality rate among motorcyclists increased from 416 to 585. According to the data presented, 70% of serious injuries resulted from a motorcyclist's head impact. Given the growing popularity of motorbike vehicles, it can be hypothesized that head injury will be the main cause of disability or death among motorcyclists in the incoming years. Mellor et al. paid significant attention to the breakdown of damage to helmets involved in accidents [3]. It was found that 23.6% of the helmets shell damage was to the front of the helmet, 21% to the rear and 53.2% to the side of the helmet shell.

The paperwork contains a review of specialist literature on head and neck injuries in motorcyclists during road accidents. Overloads acting on a motorcyclist's head may reach the highest values, for example during a motorcycle side impact with a passenger car [4]. Complex mechanisms of overload and deformation result in injuries ranging from relatively insignificant to human disability or death. Currently used head protection measures are far from perfect and in many cases do not even provide minimal head protection against the injury consequences of an accident, despite the fact of meeting specific legal regulations. Elements of road infrastructure, such as various types of poles, fasteners systems, elements of energy-intensive barriers, separating barriers, alarm columns, etc. are also significant problems. In this literature, review attention was drawn to injuries to the motorcyclists' head and neck when the helmet is under obstacle impact forces, potentially from road infrastructure elements. The biomechanics of head injuries subjected to dynamic loads have been described in many articles [5-8].

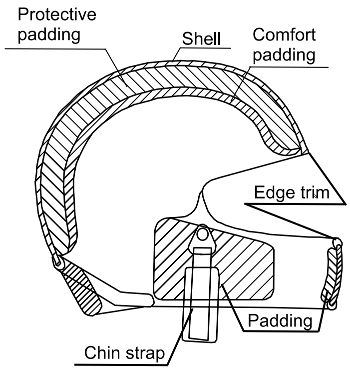

Figure 1. Basic construction of a motorcycle helmet.

The aim of the work is to systematize issues related to protective helmets used by drivers and passengers of two-wheeled vehicles taking into account the type of crash injuries. The work consists of five parts. Part 1 presents statistics related to the number of post-accident injuries [9]. Part 2 of the paper contains a general description of design solutions for currently used helmets with methods for testing them. In the third part of the article the head and neck injuries that occur during an accident when colliding with various types of obstacles are characterized. The work is summarized with the discussion and the directions for the planned further studies of the neck-head-protective helmet bite.

Modern protective helmets used by motorbike drivers and passengers have energy-absorbing functions for the following components: the design solution, the mechanical properties of the shell material, the mechanical properties of the lining and the fastening system (Figure 1).

The plastics currently used in engineering practice can be divided into popular, cheap materials and very technologically advanced composite structures. Of course, the price of the material used is important, because it influences the price of the final product and its energy-absorbing properties. Motorcycle helmets can be broadly divided into open helmets and closed helmets also called integral helmets, where the structural elements of the helmet protect the jaw. The outer shell of the helmet, which is an energy-absorbing structure, is usually made of polycarbonate, polyvinyl chloride acrylonitrile butadiene styrene copolymer or epoxy resins that are composite with aramid, carbon or glass fibre. There are also helmet shells, made with the use of Kevlar. Inside the shell there is a lining made of, e.g., EPS (Expanded Polystyrene) or other energy-absorbing materials. Modern structures of the shell of helmets are built as composite layered structures.

2. Statistical research review

When starting a literature review on the protective qualities of helmets, it is important to look at the mechanism of injuries in accidents. Hurt et al. paid attention to the head injury mechanism among motorcyclists using protective helmets and among motorcyclists without head protection against the effects of accidents [10]. The differences in the injury mechanisms are as follows: contact and inertia injuries are typical of accident victims without helmet protection, inertial injuries pose a particular risk to motorcyclists wearing a protective helmet. It was also noted that the rotational load injuries on the brain can be reduced, but cannot be completely ruled out.

Many statistical works are devoted to the analysis of traffic accidents in relation to specific countries and agglomerations. Grimm et al. analyzed data on accidents in Delhi, India among motorbike drivers [11].

It was noted that not all drivers protect their heads with a helmet. As a problem solution, the implementation of training, increasing awareness of the danger among motorcycle users and development of road infrastructure was proposed. The study concerns the city of Hyderbard in India, where the relationship between the number of fatalities among motorcyclists and the popularity of using protective helmets was investigated [12]. It was pointed out that youth drivers are more prone to not using a protective helmets and risky behavior. Research has shown that better educated people use helmet head protection more often. The researchers came to interesting conclusions based on the example of Vietnam, showed that motorcycles without the required qualifications have a lower accident rate [13]. It was also noted that the longer drivers' experience, the more accidents occur. Another study was conducted in Vietnam [14]. Authors showed an increase in the popularity of protective helmets among motorcycle users from 30% to 93% and the effectiveness of head protection with helmets both in terms of the extent of injuries as well as paying attention to the social costs. The increased popularity of head protection with a helmet is due to legal regulations.

The diverse view of the researchers related to motorcyclists' accident rate allows the problem to be assessed in terms of various criteria. At work authors present to the influence of weight and cut of helmets and clothing on injuries of motorcycle passengers (people following the driver were subject to research) [15]. The research was conducted in Pakistan in the city of Lahore. The authors drew attention to the need to introduce structural changes in both protective clothing and protective helmets, and to raise awareness of safety among motorcycle users. Many researchers emphasize the need for training and campaigns for road safety. Authors of the paper using questionnaire data from Taiwan, try to assess the extent of injuries in motorcyclists depending on the type of protective helmet [16]. It was noted that the severity of the injuries is influenced by the type of protective helmet. Full face helmets showed the lowest degree of injuries. The results of the survey conducted in Malaysia by Roszalina et al. formed the basis for finding a link between head injuries and the protective helmet and its fastening system [17]. The popularity of repaired helmets was noted. It has been found that the effectiveness of the fastening system of the protective helmet plays a more important role in the accident than the type of helmet. Similarly, the research conducted in Malaysia, proved the impact of motorcycle helmet design features on head trauma [18]. The problem of facial injuries was clearly highlighted. The summary is that the protective helmet fastening system is more important than the type of helmet and has a decisive influence on the protection of the head in an accident.

Statistical research also includes considerations in the context of applicable law. For example, Jones et al. noted that in the United States, not all states have an obligatory legal regulation to wear protective helmets [19]. Despite 30 years of pressure from the federal government, there is still no unified regulation. Interested statistical data on the accident rate among motorcyclists up to 24 years old and between 45 and 54 years old in California State (US) were presented by Jung et al. [20]. The lack or improper use of protective helmets was noted as the cause of the head injuries. Solutions to increase the safety of motorcycle users were proposed: training, promoting safe driving and enforcing the applicable law. Legal regulations and raising awareness of road safety are key factors that can improve accident statistics. Ouellet J., using reconstructions of motorcycle accidents in Los Angeles from 1976-1977 and Thailand from 1999 – 2000, try to assess many factors affecting a motorcycle accident, including the assessment of head protection with a helmet [21]. He noticed that there is no reason to justify that the use of a protective helmet results in riskier behavior by motorcyclists while riding. The opposite argument appears among people skeptical about legal regulations obliging the use of head protection with a helmet. Statistical data from the states of South Carolina, Indiana, Florida and Hawaii showed the effectiveness of head protection with helmets among moped users [22]. Legal regulations are also subject to scientific evaluation. Peng et al. assessed the applicable legal regulations in the context of the use of helmets among motorcyclists in the United States [23]. It was noted that in 2013, the number of motorcycle users who wear a protective helmet has decreased in the United States. It is worth noting that the applicable legal regulations have a direct impact on the protection of the head by motorcyclists. The non-use of protective helmets by motorcyclists in the United States who use legal possibilities of the regulations were described in [24]. Changes in federal regulations have been proposed, which may contribute to the popularization of head protection with a helmet among motorcycle users. Eltorai et al. using the example of the United States, analyzed the problem of road accidents among motorcyclists [24]. An attempt was made to persuade changes in legal provisions to protect the head with a helmet in an obligatory manner. Attention was paid to the social aspect and the costs of treating victims of accidents. The effects of waiving the obligation to use motorcycle helmets on the example of the state of Pennsylvania were described in [25]. It was noted that the repeal of the provisions related to the obligation to use protective helmets significantly increased the number of fatalities among motorcyclists. The problem of the widespread use of uncertified helmets by motorcyclists was discussed by Tsui et al. [26]. The research was conducted in California, United States. An interesting result of the research is the statement that users of BMW motorcycles often use safety helmets without certification, users of Harley-Davidson motorcycles choose certified safety helmets. Federal regulations and changes to the safety standards for motorcycle helmets were listed in [27]. Data on the number of accidents, injuries of victims using a protective helmet or not protecting their head with a helmet and using non-certified helmets were summarized. It was noted that uncertified helmets provide much worse head protection in an accident.

The factors influencing motorcycle accidents and the risk of injury were analyzed by Kun-Feng et al. [28]. In the data analysis, a risk matrix was used and an attempt was made to answer the question: how to improve the situation of motorcyclists in road traffic? Interesting research has been undertaken by Taryn et al. [29], where authors have tried to find a link between helmet type and neck injury, and helmet type and head injury. The research was conducted in California. It was noted that the type of helmet (full face, open) had a large impact on the head injuries in the event of an accident. It is worth noting that there was no correlation between the type of helmet and the injured neck of the injured person. Moreover, the researchers found that the type of protective helmet was strongly associated with the incidence of victim head injuries. It was noted that the type of protective helmet did not affect the rider's neck trauma. Roehler et al. draw attention to the issue of awareness among motorbike drivers and passengers regarding the protection of the head with a helmet, was developed on the example of Cambodia [30]. Attention was drawn to the need to raise awareness of the traffic safety and security of passengers using motorized two-wheelers. The results of the analysis of data collected in the United States over a period of 33 years were presented in [31]. An attempt was made to assess the legal changes relating to motorcycle helmets. Counterarguments for the supporters of the use of protective helmets were put together. An example is the finding that helmets do not provide effective protection in an accident and increase the risk of neck injury. It was pointed out that motorcyclists can argue their beliefs by stating that protective helmets reduce the visibility of the vehicle driver. It was also noted that the compulsion to use protective helmets may contribute to riskier riding by some motorcyclists. The authors point out the need to raise awareness in the field of road safety and to look for solutions encouraging to protect the head with motorcycle helmets. A yearly study concerns the assessment of fatal injuries among motorcyclists in the context of the type of protective helmet in California was presented in [32]. The research results clearly show the relationship between the extent of head injuries and the type of motorcycle helmet. Attention was paid to helmets without appropriate certificates. The authors suggest that the police, after appropriate training, can inspect protective helmets used by motorcyclists and eliminate helmets that do not meet the legal criteria.

The analysis of scientific studies in the context of the assessment of the protective qualities of motorcycle helmets was described by Rice et al. [33]. Particular attention was paid to publications questioning the lack of influence of a motorcycle helmet on the trauma of a motorcyclist's neck. According to the authors, the most popular and frequently cited source questioning the lack of correlation between the helmet used and neck trauma is Goldstein's work from 1986. The results presented by Golstein are often used as arguments against the use of motorcycle helmets. Opponents argue that safety helmets can cause neck injuries in an accident due to their weight. The authors of the article analyzed Goldstein's work and, using new statistical methods, found a number of errors in Goldstein's work. The authors of the study show that the use of protective helmets by motorcyclists evidently protects against fatal head injuries, while also protecting to some extent against neck injuries in an accident. The accident reports in Thailand and Los Angeles for fatal injuries among motorcyclists wearing a helmet and not wearing a helmet at the time of the accident were described in [34]. Authors conclude that using a motorcycle helmet can cause fatal neck injuries. Moreover, according to the authors study, the motorcycle helmet is very effective in preventing death and serious brain damage, but in motorcyclists with non-life-threatening neck injuries. The Abbreviated Injury Scale (AIS) injury rate by using the example of accident data among Los Angeles and Thailand motorcyclists was estimated. The authors also analyzed photo documentation of motorcycle accidents. It was noticed that motorcycle drivers who did not use a helmet were exposed to injuries 2 - 3 times more often than drivers wearing a helmet. The researchers said the helmets were extremely effective in countering brain injury and death. At the same time, it was noted that, in addition to the protective function of the helmet, many accident victims die as a result of injuries to areas of the body below the neck. Gwan-Jin et al. try to answer the question of whether using a motorcycle helmet can reduce whiplash injuries (cervical spine injuries) [35]. Clinical tests control studies were conducted and data obtained from the emergency department were used. The AIS injuries were assessed in the period from 2011 to 2016. The authors concluded that the use of a helmet by motorcyclists, apart from protecting the head, also improves the safety of the cervical spine. Reading publications related to neck injury among motorcyclists wearing a helmet shows clearly divergent conclusions. Some researchers believe that the helmet does not affect neck trauma, others argue the opposite. The results of studies obtained on the basis of the conducted sections of the head and neck among fatalities in motorcycle accidents in Thailand were presented in [36]. The aim of the authors was to evaluate latent injuries, paying special attention to injuries of the soft tissues of the neck, i.e. hemorrhage from the vertebral and carotid arteries. The scale of AIS injuries and the scale of severity of ISS injuries were determined for each examined case. The authors of the study point out that both motorcyclists wearing a protective helmet during the accident and motorcyclists without a helmet showed a high frequency of latent neck injuries, such as hemorrhages in the cervical sheath or around the vertebral arteries, the diaphragmatic nerve or the brachial plexus. It was also noted that in some cases injuries to the cervical vertebrae or the spinal cord occurred. The authors of the study note that they identified severe internal neck injuries despite the lack of external physical evidence of neck injury. Mau-Roung et al. point out that motorcyclists are 34 times greater risk of an accident than other motor vehicle users [37]. It was also noted that limb injuries are typical for all victims of motorcycle accidents, while head injuries occur most frequently in fatal accidents.

The impact of the type of helmet (full face helmet, open face helmet and half-covering helmet) on injuries sustained by motorcyclists who have suffered accidents was presented in [38]. The study involved the assessment of accident helmets and the information was collected in a village agglomeration in Korea. The authors compared the results of research on crash helmets with the injuries of motorcyclists who did not have helmets at the time of the accident. The AIS injury scale was used to evaluate the tested helmets and the consequences of accidents. The degree of head protection has been shown to vary depending on the type of protective helmet. It turns out that the popularity of head protection with a helmet is not unequivocal. Li-Ping et al. noted that in smaller cities of developing countries, the popularity of using protective helmets among motorcyclists is not the highest [39]. Based on data obtained from two cities in China, the researchers tried to assess the awareness of the risk in a motorcycle accident. It has been found that weaknesses in law enforcement and a lack of awareness among motorcyclists are factors that have influence to the consequences of motorcycle accidents. Orsi et al. surveyed the opinions of motorcyclists about protective helmets who were involved in a road accident and motorcyclists who were not involved in the accident [40]. When collecting information about the rider, motorcycle and protective helmet, it was noticed that most riders were dissatisfied with their helmets. The reasons for the dissatisfaction were the noise and the helmet's visor.

The problem of head protection does not only concern motorbike and moped drivers. There are also accidents among bicycle users resulting in head injuries. Assess the protective benefits of bicycle helmets on the Sweden example were presented in [41]. The use of bicycle helmets has been found to reduce the risk of serious head injuries. The problem of cyclists' safety was looked at as a whole, analyzing the system: car, road, cyclist, protective solutions. Similarly at work [42], based on data from Germany, the safety of cyclists and the causes of accidents involving cyclists were assessed, paying particular attention to the impact of alcohol consumption by bicycle drivers and the use of protective helmets. Attention was drawn to the need for training and information campaigns to raise the awareness of safety among cyclists. Bil et al. highlighted injuries among cyclists involved in accidents based on the Czech Republic data [43]. It has been found that bicycle helmets provide little protection against the effects of high-energy accidents. The authors propose training and information campaigns promoting the safety of bicycle users and the development of road infrastructure. The safety of cyclists of bicycle-motor vehicle collisions in the United States was characterized by Meehan et al. [44]. The attention was paid to fatalities among cyclists under the age of 16 and collisions with motor vehicles. Controversies were indicated with regard to the obligatory use of bicycle helmets. Otte et al. undertook to evaluate the protective effectiveness of bicycle helmets [45]. The research was carried out in Germany at accident sites involving cyclists, accident reconstructions were prepared, impact velocities were determined and injuries were assessed. The protective effectiveness of bicycle helmets was demonstrated in comparison with people who did not have a helmet at the time of the accident. A clear benefits of head protection with a bicycle helmet were presented by Dietmar et al. [46]. It was noted that among those over the age of 40, there is an increase in serious head injuries among cyclists not using protective helmets. The bicycle helmets are effective in reducing possible head injuries, but there are areas that can be improved and provide greater protection for the head due to impacts [47]. Twelve types of homologated bicycle helmets were tested. The tested bicycle helmets hit the surface of a flat anvil with a speed of 6.5 m/s. It was shown that some of the tested helmets did not provide adequate protection in a situation where the impact took place outside the test line in accordance with the approval regulations.

Specialist literature also includes studies in which researchers consider the safety issue of the entire body of a motorcyclist. de Rome et al. note that, despite the obligation to protect the head with a helmet, few motorcycle and scooter users protect the other parts of the body properly [48]. Research was conducted in Australia. Attempts were made to find the reason for the popularity of protective clothing among some motorcyclists and the lack of interest among others. Researchers found that the reason for the lack of interest in protective clothing is low awareness of the effects of motorcycle accidents and a lack of faith in the effectiveness of protective clothing. Attention was also drawn to the need to work on protective clothing suitable for motorcyclists in warm climates. An interesting solution is the use of airbags to protect motorcyclists [49]. In the paper [50], it has been pointed out that a lot is known about motorcycle helmets, while in the case of protective clothing for motorcyclists, the aspect related to the reduction of injuries in accidents is still an area of knowledge. Researchers sought to find a link between motorcycle usage, protective clothing, and injuries sustained in road accidents. Based on the research, it has been shown that motorcycle clothing significantly reduces the severity and risk of injuries in accidents. The authors of the study propose to promote the use of protective clothing among motorcyclists through various social campaigns and legal tools.

3. Analytical, experimental and numerical research review

The scientific literature devoted to the issue of head protection with a helmet is rich and apart from statistical research, you can find many studies using simulation, modeling and experimental methods. The considerations concern both the problems of overload acting on the head, as well as material, construction and homologation tests. Deck et al. point out that in order to assess head protection systems, i.e. protective helmets, it is necessary to know the impact phenomenon in terms of impact velocity and impact angle [51]. It is also important to be able to assess the brain's resistance to overload. The need to improve the currently used bicycle helmet testing procedures in terms of impact mechanics and the assessment of brain trauma has been noticed. The paper presents the results of a large number of experimental crash tests carried out on various types of bicycle helmets. A number of computer simulations were also carried out. The authors note that the most unfavorable are linear-lateral and oblique blows, which result in the head rotating around the vertical axis. Researchers argue that the head rotates on impact as a very negative phenomenon that causes hard brain injuries. Thom et al. presents the results of tests of popular helmets in accordance with the DOT and Snell M85 guidelines [52]. Helmets were tested using the most popular impact surfaces. The deviation from the DOT standards for a large number of tested helmets was noted and there was a significant deviation from Snell standards for helmets presumably qualifying for the Snell standard. The authors showed that DOT-compatible helmets are more effective. There was a difference in the DOT and Snell tests and the reasons for the different behavior of the helmets during the tests. There was an obvious conflict between the DOT and Snell standards.

Newmann et al. presented protective limits for motorcycle helmets such as: impact speed, head protection area, impact energy, type of injury, impact surfaces and number of impacts [53]. Problems with protecting the head with a helmet related to high-energy impacts on very soft or very hard obstacles, sharp obstacles as well as rotational loads and repetitive impacts were indicated. Numerical methods are often used in the durability tests of helmets. Mills et al. presents the results of tests of bicycle helmets using the finite element method for an oblique impact on a helmet [54]. Linear and angular accelerations of the head model were assessed. The authors analyzed the rotation of the helmet in relation to the head, modeling the effects of the fastening strap. The phenomenon of friction was taken into account and the results were compared with the experimental data. Two types of protective helmets were tested, simulating an impact on different places of the helmet shell for different tangential speeds. The same authors presented the results of research after a head obliquely hitting the road. Linear and angular measurements of the acceleration of the head model equipped with a supple skin and a wig were carried out. The results obtained during the experimental tests were used in modeling with the finite element method [55]. Yogananda et al. used an adult male head model for finite element analysis under acceleration and deceleration impulse loading [56]. The worked-out head model simulated the skull with linear-elastic mechanical properties, the cerebrospinal fluid as the hydrodynamic material and the brain as the linear visco-elastic material. On the basis of the obtained results, it was suggested that angular velocity may be a better measure of the assessment of brain biomechanics than the maximum value of acceleration or deceleration. It was noted that the shape of the load impulse influences the regional stresses in the brain. Brands in his doctoral dissertation presents the research on the biomechanics of head injuries resulting from an impact [57]. The mechanism of the impact on the head was divided into the mechanical part, where the behavior of the brain is considered, and the traumatic part, where the process of injury arising is analyzed. The research was carried out using the finite element method, demonstrating the great usefulness of this tool in the study of the mechanical response of the head subjected to impact loads. Attention is also paid to the medical aspects and the usefulness of physical and analytical models in the study of dynamic loads on the head, where wave phenomena and, for example, the problem of modeling the mechanical properties of biological tissues are important. The author notes that advances in research on the mechanics of headbeats may contribute to the assessment of the risk of injury due to specific impulse stimuli.

Ptak et al. undertook to assess the safety of unprotected people who are users of the road infrastructure [58]. It was pointed out that about 50% of road fatalities are unprotected people. Existing European regulations were analyzed with regard to the safety of pedestrians, cyclists, children on bicycles and motorcyclists. The author compiled the current safety requirements for unprotected road users and compared with the results of his own research, where attention was paid to the biomechanics and kinematics of the head during an accident involving an unprotected person. The research used numerical methods and proposed changes that may contribute to increasing the safety of vulnerable road users. The imperfections of approval tests conducted in accordance with the ECE 22.05 guidelines for motorcycle helmets were presented by Pratellesi et al. [59]. The finite element method was used to simulate the tested helmets, showing the weak points of the certified helmet structures. For example, the value of the HIC parameter as a result of the authors' research was over 30% higher than the index developed on the basis of the ECE 22.05 study. The test results presented by the authors undermine the homologation procedures, because the obtained values exceed the safe range, exceeding the permissible tolerance fields. Authors of experimental results proved that the rider's head is the part of the body that gets injured most often [60]. Researchers focus on the head-inside interaction of the helmet during impact. Based on data from real accidents, the motion kinematics was simulated in the MADYMO software. The use of the finite element method allowed for the reflection of the impact phases of the head model protected by a numerical helmet. During the test, the speed of the head protected by the helmet in relation to the struck structure was taken into account in the range from 25 km/h to 60 km/h, taking into account the tangential components of the impact. It was noticed that the deformation of the motorcycle helmet shell varied from 17% to 90% for low energy impacts. The conclusions of the authors of the study suggest work on improving the dynamic properties of the helmet in order to ensure a better chance of survival at impact speeds greater than 30 km/h. Mills et al. presents the results of an oblique impact test on a full-face protective helmet [61]. The research was carried out using the finite element method. The authors assessed linear and rotational acceleration for the Hybrid II headform. The study took into account the phenomenon of friction between the head and the helmet lining as well as the helmet shell and the road surface. The tests were carried out in accordance with the British standard BS 6658, which is applicable to diagonal impact tests. The authors conclude that limiting the linear acceleration when the helmet shell hits the road surface can reduce angular acceleration, while improving the effectiveness of protection of the rider's head. Bonin et al. presents the results of research on the impact of fitting motorcycle helmets on the effectiveness of head protection during an accident [62]. The authors noted the inconsistencies between the size of the head and the fit of the protective helmet used. Improperly matching the size of the motorcycle helmet affects the HIC head injury criterion value. Impact tests on the front of the helmet were carried out at a linear impact velocity between 2.0 and 10.5 m / s. After testing, the helmets were scanned to determine residual deformation. Butz et al. undertook research on the impact of accessories such as a camera attached to the shell of a bicycle helmet on head injuries during an accident [63]. The tests were carried out on a laboratory stand and the head loads were measured. The head hit was against a flat steel anvil. It was noted that the helmet-mounted camera may reduce the load on the head during an impact. During the research, the camera holder was not damaged and it was found that further tests are necessary. On the basis of the obtained test results, no increased risk of head injuries was found when hit by a helmet with a camera mounted.

4. Materials and construction

The study on the development of protective and motorcycle helmets is an inspiring source for understanding issues related to head protection. The ingenuity and versatility of researchers and designers is reflected in the systematic development of security systems. The history of the development of protective helmets over 50 years was compiled in [64]. Authors focused to the aspect of biomechanics. The development of headbeat biomechanics is presented, attention is paid to injuries related to tissue deformation (skull, brain). The author presents valuable comments for researchers of head injuries, pointing to the need to accurately reflect the physical properties of the object, taking into account three-dimensional kinematics, both linear and translational. The history of the development and development of approval standards for protective helmets is also presented. The author draws attention to the influence of rotational motion on head trauma as a very important factor that can be a reference point for new motorcycle helmets designs.

The possibility of increasing the efficiency of energy absorption by motorcycle helmets, through the use of aluminum in the helmet structure was presented by Caserta et al. [65]. An innovative proposal to change the structure of a motorcycle helmet consists in the use of honeycomb structures, which are the lining of the helmet's interior. Aluminum honeycomb structures were used in the prototype protective helmets and tests were carried out in accordance with the ECE 22.05 directive. The impact test results obtained for the prototype helmets were compared with their commercial counterparts. The authors point out that the proposed, innovative solution more effectively protects the head during an anvil impact simulating a curb impact. The factors affecting the scope of injuries such as improper manufacture of protective helmets and improper use of motorcycle helmets was described by Dubey et al. [66]. The authors set themselves the goal of developing an "intelligent" protective helmet, the task of which will be to monitor and transmit information about the vehicle and the person driving the motorcycle. A modernized, "smart" helmet can inform the driver about the traffic situation, thus helping to make the right decisions. The authors point out that not wearing protective helmets by motorcyclists is very dangerous, while the use of helmets contributes to the reduction of injuries in an accident, contributing to saving health and life. According to the authors, the causes of road accidents are reckless driving, driving under the influence of alcohol and using a mobile phone while driving. Attention was drawn to the problem of promptly informing the relevant emergency services, therefore the proposed “smart” helmet solution may contribute to the improvement of accident statistics.

In a review article on the issues of head protection with a helmet the issues of energy dissipation, impact and protection of the head against injuries are presented [8]. Concepts for the development of the protective properties of helmets are discussed due to innovative technical solutions. The methods of testing protective helmets were presented and a new research approach was proposed, e.g. due to the problems related to head rotation during an impact. The authors, referring to the WHO data from 2009, point out that injuries sustained as a result of road accidents are one of the main causes of death. The review article compiled the statistics of motorcyclists' accident rates for some European Union countries, the entire European Union, Australia, the United States and Japan, showing low effectiveness of protection of motorcycle users. It was pointed out to the WHO data from 2009 that in countries where the motorcycle is the main means of transport, the death rate among accident victims reaches approx. 90%. The authors of article emphasizes that the use of protective helmets clearly increases the chances of minor injuries in accidents, while increasing the chance of survival. The paper describes various constructions of protective helmets, starting from the ancient ones, through the chronological development of technical solutions used over the years. The authors suggest that despite the technological advancement of modern motorcycle helmets, the distribution of loads over a large area of the head and the use of impact energy dissipation mechanisms, there is still area for improving the protective effectiveness of helmets. It was pointed out that the development of protective helmets does not go hand in hand with the progress in understanding the mechanisms of head injuries following impacts loads. The authors emphasize the need to research the degree of protection of motorcycle helmets taking into account the angular acceleration, arguing that the rotational movement caused by an impact with the helmet occurs in all accidents involving motorcycles. The paper discusses the following injury assessment criteria: Peak linear acceleration (PLA), Head injury criterion (HIC), Gadd severity index (GSI) and linked. The article describes modern design solutions for motorcycle helmets, e.g. with MIPS technology, where the angular acceleration of the head is reduced when hitting an obstacle. The PHPS technology is also described, the task of which is to minimize the angular acceleration of the head protected by the helmet.

The energy consumption for various types of popular helmets at different impact speeds was presented by DeMarco et al. [67]. Shock loads were directed to the side of the helmet when falling onto a flat anvil at a speed of 0.9 - 10.1 m/s. The acceleration of the head model protected by a helmet was investigated. Attention was paid to the influence of the helmet lining and foam compaction on the recorded acceleration of the head model. The results of tests of polyurethane-auxetic foams with open cells and use of which as a lining material for protective helmets allows for a better fit of the helmet and a reduction in the value of linear accelerations were presented in [68]. The experimental test involved measuring the force of an impact to evaluate the different foams of the helmet liner material. Acceleration was measured on the head model in a protective helmet, when dropped from a height so that the impact was on the front of the helmet and on the side of the helmet. Positive research results suggest further development of the concept of using auxetic materials in the construction of protective helmets. The results of experiments of energy consumption and other mechanical properties of foams that are used as lining material for protective helmets in sport were presented in [69]. The methodology of proceed during the assessment of the suitability of energy-absorbing materials as protection against impacts was presented. The results of experimental and numerical research on three types of bicycle helmets due to the ability to dissipation the impact energy in a side fall were described in [70]. The research was conducted in accordance with AS / NZS 2063:2008, the Australian/New Zealand standard for testing bicycle helmets. Experimental and simulation studies with the use of numerical methods were carried out. The aim of the research was to develop a simulation model to conduct further research. Numerical models were built after 3D scanning of head models and commercial helmets undergoing experimental testing. Both the shells of the helmets and the lining were scanned, which was the basis for the prepare of numerical models.

The study [71] is devoted to the problems of protection against the effects of impacts of delicate objects (the problem of transport and packaging). It was noted that if a sensitive object is protected, such as the head and brain or for example some delicate product inside a package during transport, the duration of the collision should be analysed in relation to the response time of the dynamic system. It turns out that relatively short impacts cause damage due to too sudden change of speed. In the case of relatively long impacts, the damage does not cause excessive acceleration. Protecting the object from the effects of impacts, you can: either limit the impact force, while increasing the impact duration, or conduct a controlled dissipation of the impact energy. The authors present that both methods of protection against impacts can be applied through the use of viscoelastic materials. Researchers reported head injury criteria by impact: a Wayne state tolerance curve described with an approximate velocity change of about 4 m/s for very short strokes, a maximum acceleration of 40g for longer strokes, and a characteristic impact period of about 10 ms. It was noted that other criteria for brain injuries have similar features but are complicated due to the non-linear biomechanical characteristics of the brain and the complexity of the characteristic periods. As shown in the literature review above, road safety is a result of many factors. Protection of health and life also depends on the road infrastructure, the technical condition of the vehicle, weather, psychophysical conditions, etc. Savino et al. developed an overview of active safety systems used in two-wheeled vehicles [72]. The study focuses on: ABS systems used in two-track vehicles, autonomous emergency braking system, collision avoidance systems, infrastructure solutions for intersections, intelligent transport systems, corner warning systems, human-machine interface solutions, driving stability control and traction control systems, visionary. In the paper [73] authors presented the results of biomedical research related to lateral impact injuries, paying attention to the individual age. The presented research results may contribute to the improvement of automotive safety systems, such as side airbags, and the improvement of the criteria for the assessment of injuries. The authors pay attention to a number of individual factors in elderly people and analyze the overload affecting individual parts of the body. Accelerometers were mounted in the middle part of the head, at three points in the spine section and at three points on the dummy's chest. The authors report the need to conduct research on the impact of side impact loads on the elderly, which may translate directly into the improvement of currently used safety systems in passenger cars.

The problem of protecting the head and other parts of the body against the effects of impact loads is also actual in sports. In the scientific literature, you can find many studies on the safety of athletes. The mechanisms of head injuries on the example of footballers was described in [74]. The authors paid attention to two types of problems that may occur during head trauma testing. Currently, new indicators for head injuries are being developed from football injury data [75]. The first type of problem results from the use of research equipment, i. e. accelerometers and the measurement data acquisition technique, the second problem arises from the data transmission system related to the recording of the kinematics of the impact in the head, neck and torso system. The authors presented the measure methodology error values, they estimated during the study of falls and collisions among footballers. The results of tests of linear and angular accelerations and pressures for protective helmets used in football were included in [76]. Experimental studies were compared with the results obtained on the basis of data recorded from sensors mounted in the helmets of players and volunteers. The use of protective helmets in equestrian sports improves the safety of riders, but concussions in the event of falls are still a problem [77]. Equestrian helmets are designed with a focus on certification requirements, where the fall of the helmet onto a rigid flat surface is tested. The authors of the study point out that most of the falls in equestrian sports are falls on a flexible surface with an oblique head impact. The authors conducted the research in accordance with the recommendations of the standards marked as EN1 and EN2 and reflecting the actual conditions of the riders' falls. Attention was drawn to the differences in the duration of the impact during tests in accordance with the recommendations of the above-mentioned standards and the impact on a deformable surface, e.g. a turf.

The need to protect the head was the first most likely to arise in the military. From ancient times, helmets were used to protect the head against injuries during fights [78]. Currently, the issues related to the protection of a soldier's head are still a cognitive aspect. A series of inspiring research is underway to improve the safety of soldiers. The problem of head and neck injuries among soldiers whose vehicle has run into an explosive device, where the blast of the shock wave causes the soldier's head to hit the roof of the military vehicle were described in a paper prepared by M. Franklyn and S. Laing [79]. The authors presented the results of research on the interaction between the head model, the type of helmet and the internal surface of the vehicle roof under the vertical load effect. The test methodology was based on the use of a special device and hitting the head model against a steel sheet at various configurations and impact velocities. Different types of safety helmets and vehicle roof lining materials were assessed. The HIC criterion determined for each impact was used as a criterion for head trauma. It has been noted that the head injuries are significantly lower with the use of a suitable safety helmet than with the use of the inner lining of the vehicle roof. The results of an experimental study of ballistic injuries of the head and brain were presented in [80]. The head models were made in the form of spherical heads filled with gelatin and Sylgard imitating substances (silicone elastomer). The head models were subjected to pistol bullets of popular geometric dimensions. Four pressure sensors were used that recorded data at a frequency of 308 kHz. A fast camera was also used, which recorded the examined dynamic phenomenon at a speed of 20.000 frames per second. Based on the obtained results, the authors concluded that Sylgard adequately models the brain tissue.

5. Head injuries – statistics in Poland

Due to the Poland latitude, the motorcycle season starts in April (average temperature approx. 7 degrees Celsius) and ends in October (temperature 8 degrees Celsius). In 2019, 2630 accidents involving motorcyclists took place on Polish roads and 295 people (including passengers) were killed. The most tragic in terms of accidents are the summer months: June-August (1.293 accidents, 146 fatalities) [9].

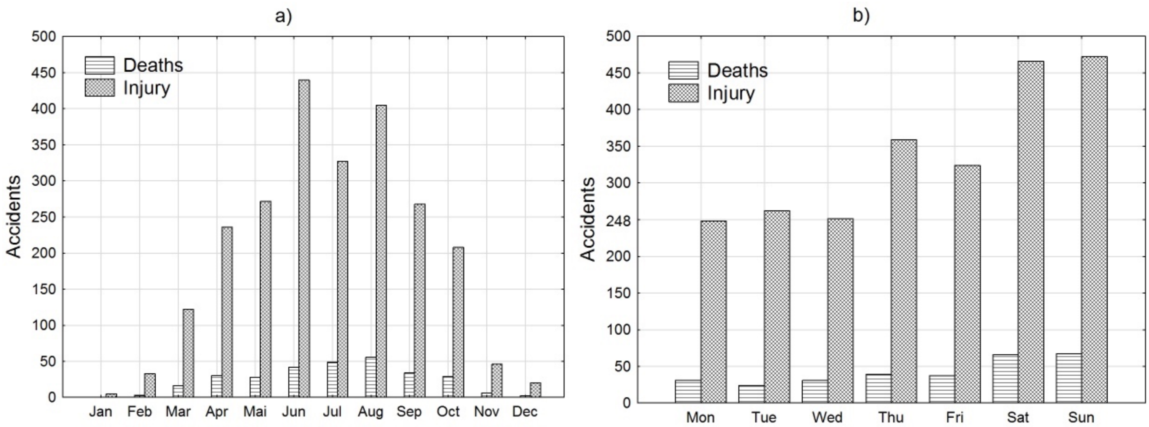

Figure 2. Number of accidents a) monthly in year scale b) a week scale.

In the Figure **2,** the number of motorcycle accidents is presented. The peak took place on Saturdays and Sundays (1010 accidents, 133 victims - 45.1% of all victims). 1350 accidents (51.3%) were caused by car drivers, while 1082 (41.1%) were caused by motorcycle drivers. In the first case, the main reason was the failure to give way - 933 accidents (69.1%), in the second case, the inability to adjust speed to traffic conditions - 594 incidents (54.5%). The greatest threat is posed by motorbike drivers aged 25-39, who have caused 450 accidents (41.6% of the total due to motorcyclists' fault).

6. Head and neck spine injuries

The direct effect of head injuries can bring damage to the structures like the soft tissue covering a skull, skull bone architecture, and intracranial structures like brain and meninges. In most cases there are injuries within the structure and without contact with the external environment. However, open injuries happen as well. The damage can be divided into general (e.g., DAI – Diffuse Axonal Injury), and focal (e.g., hematomas) together with satellite one (ocular symptom). After-effects of injuries are categorized into early (e.g., traumatic brain edema) and late ones (e.g., post-traumatic epilepsy). Minor cerebral hemorrhagic foci located within the cerebral cortex are common. Their characteristic feature is the polarity of their arrangement They form at the place of injury and on the opposite site, with greater severity, as a result of a contrecoup mechanism. Rapid deceleration predisposes to inertial injuries. Linear acceleration predisposes to rupturing of bridging veins (subdural hematomas), while angular acceleration does so to deeper cerebral structures (soaring hemorrhagic foci) [81],[82]. Cutting forces at the edges of hypothetical brain layers caused by angular acceleration led to breaking of axonal connections, which results in DAI. According to Gennarelli, the most common form of acute subdural hematoma (ASDH) is caused by shearing of veins that bridge the subdural space [83]. The severity of injury associated with bridging vein rupture has led to numerous studies of their mechanical properties [43], [44]. Other important phenomena are also intracranial bleedings. In terms of etiology bleedings are divided into epidural, subdural, subarachnoid, intracerebral, diffuse, and intraventricular. Epidural hematomas usually form as a result of active and passive injuries, most commonly after meningeal artery ruptures. They take lenticular shape. Subdural hematomas are usually implications of ruptures of bridging veins caused by passive and accelerating injuries. They tend to take the shape of a crescent. Consequences of hematomas are intussusceptions and intracranial compartment syndrome caused by the formation of extra volume in the skull cavity [81], [84]–[87].

In comparison to the other traffic participants, motorcyclists are more vulnerable to severe body injuries [88]. The probability of death as a result of motorcycle accident is between 30 to 44 times greater and the likelihood of being severely injured is from 20 to 56 times bigger, in comparison to other vehicles and relative to the distance traveled [35], [88]–[92]. The factors, which have been proven to have an influence on the severity and type of injuries are: speed, age of the driver, alcohol, psychotropic drugs, time of day, traffic volume, atmospheric conditions (including visibility), road environment (including the existence of safety barriers at the road), inrun position, approach angle, body position at the time of impact, type and weight of the bike, and protective clothing [81], [87], [92]–[97]. Head injuries are the reason of almost half of the fatal accidents; therefore, they are the most common lethal injury [98]. In fatal accidents spinal damage is mainly located in its cervical area [99].

A detailed analysis of motorcycle accidents with a fatal result in the years 2001-2010 in the Poznań region (Poland) indicates the most frequently sustained injuries. Death on the spot occurred in over 60% of the victims. Head injuries occurred in over 82.5% of fatalities, with isolated craniocerebral injuries accounting for 34.7% of fatal injuries, which was the highest result among internal injuries. The most common head injuries were: haemorrhages in the soft tissues covering the skull (54%), fractures of the skull base (42%), bleeding into the ventricles (33%), and fractures of the craniofacial bone and cranial vault. Subdural and subarachnoid hematomas occurred in 28.6% and 22.2% of cases, respectively. Injuries to the neck and cervical spine were found in 58.6% of cases. The most common were haemorrhages in the neck muscles (42.9%), laryngeal cartilage injuries (19%), dislocation in the atlococcal joint (14.3%) and cervical vertebrae fractures (6.3%) [100].

Helmets are fundamental passive pieces of protective gear. They greatly reduce the risk of severe and fatal injuries [81], [98], [101]. However, Lloyd indicated that motorcycle helmets are only 37-42% successful in preventing fatal injury [102].

Injuries caused by accidents without participation of other vehicles differ depending on the type of the accident. They can be categorized as low side and high side. When it comes to the gliding of the body along the road because of the friction force connected with it (dominant in low side) the most common wounds are abrasions. Avoiding them is possible by wearing a special protective clothing along with a helmet. In case of the motorcyclist being flipped over the handlebar (high side) usually the most dangerous aspect is the fall. The following gliding along the ground is in this case a secondary aspect. The main factor influencing the damage upon falling to the ground is not the height, but the speed at the critical moment of losing control of the vehicle. The high side can be far more hazardous, especially when it comes to head traumas. In this case the use of a protective helmet plays the key role in preventing potential head injuries. Additional factors that increase the risk of heavy injuries are objects in the surroundings (e.g. guardrails - road safety barriers), which a driver can slam into, and the probability of them getting hit by their own motorcycle [81].

When it comes to colliding with road safety barriers almost half of the casualties suffer head traumas, despite using protective helmets [103]. This indicates that the severity of the collisions in many cases exceeded the functional range of the helmets. Bambach et al. concluded that damage to the cervical spine caused by hitting the road safety barriers represents from 3 to 20% of all of the injuries, although they very often contribute to the increase of the death rate among motorcyclists [89]. There have also been cases of tetraplegia caused by a cervical fracture as a consequence of hitting a road barrier post with the head, even while wearing an integral helmet.

Among the most common post-accident injuries there are head and brain traumas: subdural hematomas, epidural hematomas, skull vault fractures, skull base fractures, overall damage to craniofacial structures, hemispheres of the brain, cerebellum and spinal cord [81], [85], [104]. Damage to spine can result in vertebral fractures (mainly compression ones) and spinal cord injuries, including its rupture, typically in the cervical spine.

Most deaths of motorcyclists are caused by head injuries, therefore wearing a helmet is a basic precaution allowing to reduce the percentage of traffic accident fatalities [95], [105]. Wearing a protective helmet has been proven to have a positive impact on the risk of hospitalization, serious injuries and accident-related mortality [101], [103], [105]-[106]. Research proves effectiveness of helmets showing that they reduce the risk of death by 29% to 56% [35], [107]-[111]. It has also been showed that using helmets lowers the probability of brain damage by up to 69% [101], [112]. Motorcyclists who do not use helmets are 2,4 times more subject to head damage and are 3,1 times more likely to die as a result, when comparing to the people, that use helmets [95], [105], [113]. An important factor determining the effectiveness of protection is the type of a helmet. Integral helmets (full-face), jaw helmets (full-coverage) and open helmets (half coverage) are the most effective types, which offer the best protection. The differences in the efficiency of these types are not precisely defined and require further research [109], [114], [115]. However, there are reports of the superiority of integral helmets over other types [110]. Preliminary attempts to systematize helmet safety levels indicate that after integral ones, jaw and open helmets might be the next best options when it comes to safety [29]. Open helmets do not protect against injuries of the facial structure. This type of injury can also occur while wearing an integral helmet -- at very high speeds and with specific impact points (e.g. car roof edge) [81]. Legal regulations imposing the required level of helmet safety confirmed by approvals allow to specify standard helmets that meet these conditions and non-standard ones in relation to those that do not meet safety requirements [95]. Non-standard helmets have a 3 times higher risk of head injuries than integral ones [29]. Despite the protective role of the helmet, accidents at high speeds may cause brain injuries due to rapid movements inside the skull [116]. This is caused by the transfer of energy to intracranial structures [81]. The risk of head injuries is greater the faster the vehicle goes at the time of the accident, and the older the driver is [29]. Analyzes conducted in Norway indicate a relationship between the use of bicycle helmets and a higher risk of dentoalveolar injuries [117].

An equally important aspect as the helmet type, which directly translates into safety, is the correct fit and attachment to the head [110], [118]. There are reports claiming that proper attachment of the helmet is even more important than its type when it comes to the protection against head injuries. The right fit and fastening of the attachment strap play an especially important role. An incorrectly fastened helmet can fall off the driver's head during a high-speed accident [119]. In the case of the helmet falling off, the risk of head injury increases 5-fold and the risk of severe head injury that could be fatal end 4-fold [110].

Additional factors associated with safety helmets are their influence on view and audibility. The negative impact on the mentioned factors was defined as fairly small in relation to the benefits of using a helmet [120]. The influence of a colour of the helmet on the risk of an accident is also worth mentioning. It has been shown that a white helmet combined with reflective clothing reduces the risk of an accident [121]. It is also shown, young drivers have a higher risk of serious injury, including head injury, and death in an accident [122].

Spinal and spinal cord injuries in the cervical segment represent only 1% to 11% of all injuries. However, they are the ones mainly responsible for mortality and disability [103]. There is a lack of clear evidence regarding the role of a helmet at protecting the cervical spine. There have been reports of a significant increase in the risk of injury to the cervical spine as a result of an additional weight of the head with the helmet on [123]-[125]. However, the current trend indicates a departure from this theory. Reports on the absence of this relation are in the majority of studies [126]-[129]. No relation between the type of a helmet and the probability of a cervical injury has been proven either. Factors that have a significant impact on that probability are age of the motorcyclist, alcohol, type of the accident, and the speed at the moment of the impact [29]. In addition, there have been some statements that the opposite could be possible, helmets might be playing a role in protecting cervical spine [111], [130]. The hypothesized protective function of a helmet is preventing the neck from bending excessively, beyond its natural limits [103], [131].

Figure 3. The helmet after hitting a barrier element.

Figure 4. The helmet after hitting a barrier element - broken helmet visor.

7. Discussion

The increasing number of road users and faster single-track vehicles traveling on public roads result in an increase in the number of road accidents. The prepared literature review may constitute a reference point for researchers dealing with road safety. The research work was divided into statistical, experimental, simulation and analytical. Described problem was considered in medical and technical aspects. The authors presented also actual results of construction works and helmets testing. The abundance of statistical studies allows for general and detailed assessment of the problem related to head protection and injury mechanism.

Experimental and simulation papers are a valuable source of both knowledge and inspiration for seekers of new technical solutions. Scientific work on the analytical approach is limited to the mathematical description of the constitutive relationships for construction materials and biological tissues. In the area of analytical modelling of mechanical properties of materials, there is a need for further research, including experimental ones, enabling the description of complex materials with non-linear characteristics subjected to complex load states.

The purpose of a motorcycle helmet is to reduce the blunt force trauma to the head, thereby decreasing the risk of lacerations, contusions and skull fracture. Due to the advancements in the field of passive safety systems (helmets, pads, protective clothing), vehicles are safer. Yet, despite the decreasing number of road accidents each year, they are still a problem. An additional aspect is the high cost of treating road accident victims. Due to the extent of the injuries, returning to the normal functionality is often not possible, and the treatment along with rehabilitation is very long. A large number of manufacturers of protective systems, cheaper and faster production methods, competition in the market of protective systems, all result in the introduction of helmets on the market that do not meet safety standards. This is to the detriment of unaware road users.

The serious problem presented in this publication that relates to the safety of users of motorbike vehicles, is still valid and requires systematic research. The presented literature review is a medical, technical and biomechanical summary of the current state of knowledge in the field of causes and effects of head and neck injuries among motorcyclists. Attention was drawn to the need to extend the research to include the impact of the neck stiffness during hitting an obstacle with a head protected by helmet. Noteworthy is also the need for a scientific look at the commonly installed road infrastructure elements, such as: energy-absorbing barriers, separating barriers, communication columns, poles, etc. – construction elements that pose a threat to motorcyclists involved in a traffic accident. Figures 3-4 present destroyed motorcycle helmets after impact to the road barrier elements. The authors of the article prepare a study of motorcycle helmets taking into account the impact of the neck stiffness on overloads acting on the head. Research conducted in relation to road infrastructure elements can provide valuable information for both helmet manufacturers and people related to the issue of road accidents (e.g., training, expert opinions). Actually, the authors conducted research on helmet heads protected using their own construction testing stand, where the mechanical properties of the human body can be reflected. The research program assumes a wide range of tests in which head and neck safety can be investigated in relation to road infrastructure and human body behaviour during a crash.

Interesting research in this field was done by Fernandes et. al. [132],[133]. They proposed the applicability of agglomerated cork as padding material in safety helmets. The modeling technique was used and the results from these tests indicate that agglomerated cork liners are an excellent alternative to the synthetic ones.

8. Conclusions

Head protection, injury assessment, and the need to develop the safety of two-wheeler users, despite the wealth of available means of protection are still an actual problem. Road user safety assessment is a multi-threaded issue. Despite attempts to generalize helmet test methods through legally sanctioned approval procedures, an effective assessment of the degree of helmet protection requires further research. There were visible differences in the results obtained using various methods. The impact phenomenon is a complex interaction mechanism between bodies. Road accidents are complex in nature. It is possible to increase the protection of two-wheeler users through multithreaded system research. Improving the protective effectiveness of helmets is possible through changes in the material and design of helmets, and research methods that reflect the real conditions of an accident as accurately as possible.

Additional information

The author(s) declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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