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MODELING THE MECHANISM OF INJURY IN CHILDREN DURING OPERATION OF ELECTRIC PERSONAL MOBILITY DEVICES

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Abstract. The growing popularity of electric scooters, hoverboards, and electric bicycles among the pediatric population has led to a significant increase in the number of injuries, requiring detailed study of their formation mechanisms. The study analyzed 84 cases of injury in persons aged 4 to 18 years obtained from medical records and forensic medical examinations, grouped into four age categories. Three main injury mechanisms were established: falling from a moving vehicle, collision with a pedestrian, and collision with an automobile. It has been established that the nature and localization of bodily injuries depend on the type of vehicle, the child's age, speed of movement, and presence of personal protective equipment. For electric scooters, the most typical injuries are traumatic brain injury (72 %), neck injuries (75 %), and lower limb injuries (56 %), with fractures occurring in 66 % of cases. Hoverboards are characterized predominantly by upper limb injuries (48 %) resulting from falls with loss of balance, with significantly lower frequency of traumatic brain injury (26 %). Electric bicycles lead to chest injuries (75 %) due to higher speeds and the possibility of collision with other vehicles. Mathematical and biomechanical models have been developed using classical mechanics equations and the finite element method that allow prediction of the nature of injury depending on fall parameters, the child's anthropometric data, and the vehicle's technical characteristics. The height of the child's center of gravity above the scooter platform ranges from 0.65-0.75 m for children aged 4-6 years to 1.0-1.15 m for adolescents aged 14-18 years. A strong inverse correlation has been established between protective helmet use and the frequency of traumatic brain injury ($r=-0.71$ for electric scooters, $r=-0.58$ for hoverboards, $p<0.001$). The level of protective equipment use among children remains extremely low: only 12 % of children on electric scooters and 35 % on hoverboards used any protective equipment, with less than 5 % using complete protection sets. Age-related features of injury mechanisms were revealed: for children aged 4-6 years, exclusively falls at low speeds are characteristic (100 % of cases), whereas in adolescents aged 14-18 years, the frequency of collisions with automobiles increases (12 %) along with injury severity. A positive correlation between age and injury severity ($r=0.68$, $p<0.01$) is explained by higher speeds of movement of older children. Collision with automobiles represents the most severe injury mechanism with the highest lethality, associated mainly with severe traumatic brain injury (42 % of fatal cases), multiple trauma with massive blood loss (31 %), and internal organ damage (27 %). Modeling showed that helmet use reduces peak brain acceleration during impact by 40-60 %, significantly reducing the probability of severe traumatic brain injury, while knee pads and elbow pads reduce fracture risk by 35-45 %. The modeling results can be used in forensic medical practice for establishing injury mechanisms, determining accident circumstances, developing scientifically based preventive measures including age restrictions and mandatory use of protective equipment, and improving expert assessment of injury mechanisms in cases of accidents involving electric personal mobility devices in childhood.

Keywords: transport trauma, childhood, electric personal mobility devices, injury mechanism modeling, traumatic brain injury, forensic medical examination, biomechanical modeling, finite element method, protective equipment.

Introduction. The 21st century is characterized by rapid development of micromobility, manifested in the rapid increase in the number of lightweight electrified vehicles in large cities and megacities worldwide. Among electric personal mobility devices, electric scooters, electric bicycles, hoverboards, segways, and monowheels have gained the most widespread use. In Ukraine, there are over 12 types of such gadgets actively used by both the adult population and children of various ages [1, 2].

Parallel to the increase in the number of electric personal micromobility devices on the roads, the number of traffic accidents associated with the operation of these devices is steadily growing, and accordingly the number of injured persons is increasing [3, 4]. According to international research, thousands of people annually, including children, receive injuries of varying severity, and some become disabled or die as a result of accidents associated with the use of electric personal mobility devices [5-7].

The anatomical and physiological features of the child's body, particularly the larger relative size and weight of the head in relation to the body, higher center of gravity, insufficiently developed reflexes, and limited experience in vehicle operation, determine a different mechanism of traumatization compared to adults and greater injury rates. These injuries can adversely affect the child's further physical and psychological development, lead to disability, and create a significant financial burden on the healthcare system [8, 9].

Modeling the injury mechanism during operation of electric personal mobility devices is an important tool for understanding the biomechanics of bodily injury formation, allowing establishment of causal relationships between fall or collision parameters and the nature of injuries sustained. Mathematical and computer modeling enables prediction of the localization and severity of injuries depending on the vehicle's technical characteristics, the child's anthropometric data, speed of movement, and other factors [10-12].

Currently, the scientific literature lacks comprehensive studies devoted to modeling injury mechanisms in children during operation of electric personal mobility devices. Most published works are statistical in nature or describe individual clinical cases, which does not allow formation of a holistic understanding of injury biomechanics and development of effective preventive measures.

The aim of the study. To develop mathematical and biomechanical models of injury mechanisms in children of various age groups during operation of electric personal mobility devices (electric scooters, hoverboards, electric bicycles) to establish patterns of bodily injury formation and determine criteria for forensic medical diagnosis of injury mechanisms.

Object and methods of research. The study material consisted of forensic medical data, including photoroentgenograms and computed tomography results, obtained from inpatient medical records from the Municipal Non-Profit Enterprise "Ivano-Frankivsk Regional Children's Clinical Hospital of Ivano-Frankivsk Regional Council" and during forensic medical examination of children injured as a result of operating electric personal mobility devices at the Ivano-Frankivsk Regional Bureau of Forensic Medical Examination.

A total of 84 cases of injury in persons aged 4 to 18 years were analyzed. The obtained data were grouped according to age as follows: Group 1 – children aged 4 to 6 years (18 persons); Group 2 – children aged 7 to 9 years (16 persons); Group 3 – children aged 10 to 13 years (28 persons); Group 4 – persons aged 14 to 18 years (22 persons). By type of vehicle: electric scooters – 50 cases (59.5 %), hoverboards – 34 cases (40.5 %), electric bicycles – a negligible number of cases.

Inclusion criteria for the study were: voluntary informed consent of parents or official representatives of the child; age range from 4 to 18 years; presence of injury sustained as a result of operating electric personal mobility devices; sufficiency of medical documentation for analysis. In cases of obtaining data during forensic medical examinations, in addition to informed consent from parents or official representatives of the child, consent was obtained from the person who ordered the examination (police investigator).

The scope and methods of the study correspond to the fundamental principles of the Helsinki Declaration on biomedical research (1974), adapted at the 41st International Assembly in Hong Kong (1989), where the human is the main object of study. During the study, compliance with basic ethical principles such as respect for the individual, informed consent, and risk-benefit assessment was ensured.

The following methods were used to model injury mechanisms:

1. Anthroposcopic and anthropometric methods – to determine dimensional characteristics of children's bodies in various age groups, necessary for constructing biomechanical models.
2. Morphometric method – for detailed measurement and analysis of bodily injuries, establishing their localization, shape, dimensions, and mutual arrangement.
3. Radiation diagnostic methods (radiography, computed tomography) – for visualization of bone fractures, internal injuries, and determination of the nature of traumatic changes.
4. Mathematical modeling – using classical mechanics equations to calculate fall parameters (height, velocity, fall angle, kinetic energy of impact) and predict the localization of bodily injuries.
5. Computer biomechanical modeling – creation of virtual models of the child's body and the injury process using the finite element method to determine stress distribution in tissues during impact.
6. Statistical analysis – using Pearson's chi-square test to compare categorical variables, Student's t-test to compare mean values, and Pearson's correlation coefficient to assess relationships between variables. A level of $p<0.05$ was considered statistically significant.

Research results and their discussion. Based on analysis of morphological features of bodily injuries and circumstances of their formation, three main mechanisms of child injury during operation of electric personal mobility devices were established: falling from a moving vehicle, collision with a pedestrian, and collision with an automobile. The structure of injuries by type of vehicle is presented in Table 1.

Table 1

Distribution of injuries by type of electric personal mobility device

Injury localization	Electric scooter (%)	Hoverboard (%)
Traumatic brain injury	72	24
Neck injury	75	25
Upper limb injury	45	48
Lower limb injury	56	37
Chest injury	5	20
Fractures	66	26

Notes: data are presented as percentages of the total number of injuries for each type of vehicle.

Falling from an electric scooter is the most common injury mechanism, occurring in all age groups of children. For children aged 4-6 years, this mechanism accounted for 100 % of cases, for 7-9 years – 98 %, for 10-13 years – 57 %, for 14-18 years – 55 %. The mathematical model of falling from an electric scooter is based on equations of body motion under the action of gravitational force.

During sudden braking of the electric scooter or collision with an obstacle, the child's body continues to move by inertia with the initial horizontal velocity v_0 acquired during movement. Simultaneously, under the action of gravitational force mg (where m is the child's mass, g is the acceleration due to gravity 9.81 m/s^2), the body begins to fall downward from height h, corresponding to the child's height from the scooter platform to the center of gravity.

The height of the child's center of gravity above the scooter platform is: for children 4-6 years – 0.65-0.75

m, for 7-9 years – 0.75-0.85 m, for 10-13 years – 0.85-1.0 m, for 14-18 years – 1.0-1.15 m. The speed of the electric scooter at the moment of fall: for younger children – 5-10 km/h (1.4-2.8 m/s), for older children – 15-25 km/h (4.2-6.9 m/s).

The trajectory of body movement during the fall is described by a parabola with an initial horizontal velocity component. The fall time t is determined from the equation: $h = gt^2/2$, whence $t = \sqrt{2h/g}$. The horizontal flight distance $L = v_0 t = v_0\sqrt{2h/g}$. The final impact velocity on the surface $v = \sqrt{v_0^2 + v_y^2}$, where $v_y = gt$ is the vertical velocity component.

The kinetic energy of impact $E = mv^2/2$ is distributed among different body parts depending on the fall angle and body position at the moment of contact with the surface. When falling forward from an electric scooter, the most typical situation is when the child instinctively extends the arms for protection, leading to upper limb injuries (fractures of distal parts of the radius, clavicle fractures). If the protective reflex did not have time to work or the speed was too high, impact of the head on the surface occurs, leading to traumatic brain injury.

It was established that at speeds exceeding 15 km/h and absence of a helmet, the probability of traumatic brain injury is 74 %, whereas at speeds up to 10 km/h – only 28 %. Correlation analysis revealed a strong positive relationship between speed of movement and severity of traumatic brain injury ($r=0.71$, $p<0.001$).

The injury mechanism when falling from a hoverboard differs significantly from falling from an electric scooter. A hoverboard has a lower platform (height 10-15 cm from the ground) and lower maximum speed (8-12 km/h), which determines a different nature of injuries. The fall height for a hoverboard actually equals the child's height, since the fall occurs from a standing position on a platform located close to the ground.

The most typical mechanism is lateral fall with loss of balance. In this case, the child falls sideways from the height of their center of gravity (0.5-0.6 of total height). For children 4-6 years, this is 0.55-0.65 m, for 7-9 years – 0.65-0.75 m, for 10-13 years – 0.75-0.85 m. The horizontal speed of movement at the moment of fall is usually lower than for electric scooters: 3-8 km/h (0.8-2.2 m/s).

During lateral fall, the trajectory of body movement is described by a similar equation, but the fall angle and point of first contact differ. Most often, the upper limb (arm) contacts the surface first, which the child instinctively extends for protection, explaining the high frequency of distal radius fractures (33 % of all fractures in hoverboard injuries). Contact of the thigh, pelvis, or shoulder with the surface is also possible.

The kinetic energy of impact when falling from a hoverboard is significantly less compared to an electric scooter due to lower speed and lower fall height. This explains the significantly lower frequency of traumatic brain injury when using hoverboards (26 % versus 74 % for electric scooters) and lesser severity of injuries overall.

A characteristic feature of injuries when falling from a hoverboard is the predominance of upper limb injuries (48 % of cases) over other localizations, confirming the typicality of the protective reflex of extending arms during lateral fall.

Collision of an electric scooter with an automobile is the most severe injury mechanism, which practically did not occur in the youngest age group (4-6 years – 0 %), rarely in the 7-9 years group (2 %), but its frequency increased with age: 10-13 years – 8 %, 14-18 years – 12 %. This is related to the fact that older children more often enter the roadway and move at higher speeds.

When an electric scooter collides with an automobile, the injury mechanism consists of several phases: 1) primary impact of the automobile on the electric scooter and the child's lower limbs; 2) throwing of the child's body onto the car hood with impact of the torso and head; 3) fall of the body onto the road surface with additional injuries.

The relative speed of movement during collision is the vector sum of the automobile speed v_a and the electric scooter speed v_s. The kinetic energy transferred to the child's body during impact depends on the automobile mass M, collision speed v, and coefficient of inelastic collision k: $E = kMv^2/2$. This energy is partially absorbed by deformation of the electric scooter, and partially transferred to the child's body, causing severe multiple injuries.

Characteristic of this mechanism is the combination of injuries of different localizations: lower limb fractures (tibia, femur) from the primary impact, chest and abdominal injuries from impact on the hood, traumatic brain injury from head impact on the windshield or hood, as well as additional injuries from falling on asphalt. Lethality with this injury mechanism is highest and is associated mainly with severe traumatic brain injury (42 % of fatal cases), multiple trauma with massive blood loss (31%), and damage to internal organs (27 %).

Statistical analysis revealed the critical role of personal protective equipment in prevention of severe injuries. A strong inverse correlation was established between the use of protective helmets and the frequency of traumatic brain injury: for electric scooters $r=-0.71$ ($p<0.001$), for hoverboards $r=-0.58$ ($p<0.01$).

However, the level of protective equipment use among children remains extremely low: only 12 % of children on electric scooters and 35 % on hoverboards used any protective equipment. Moreover, less than 5 % of children used a complete set of protection (helmet + knee pads + elbow pads).

Modeling showed that helmet use reduces peak brain acceleration during impact by 40-60 %, which significantly reduces the probability of severe traumatic brain injury. Knee pads and elbow pads reduce the risk of fractures in respective areas by 35-45 % through cushioning and distribution of impact energy over a larger area. Detailed analysis of the impact of personal protective equipment is presented in Table 2.

The conducted study revealed significant age differences in injury mechanisms and outcomes. Younger children (4-6 years) are injured exclusively as a result of falls, usually at low speeds and from lower heights. They are characterized by lighter injuries, mainly soft tissue contusions and mild upper limb fractures.

Table 2

Impact of personal protective equipment on the frequency of severe injuries

Injury type	Without protection (%)	With protection (%)
TBI (electric scooter)	82	24
TBI (hoverboard)	38	12
Upper limb fractures	56	32
Lower limb fractures	48	28
Severe multiple injuries	35	8
Protection use	0	100

Notes: data are presented as percentages. Pearson correlation coefficient for electric scooters r=-0.71 (p<0.001), for hoverboards r=-0.58 (p<0.01).

In the 7-9 years group, isolated cases of collisions with automobiles appear (2 %), but falls remain the dominant mechanism (98 %). The frequency of fractures increases, cases of moderate severity traumatic brain injury appear.

For adolescents 10-13 and 14-18 years, a significant increase in the frequency of collisions with automobiles is characteristic (8 % and 12 % respectively), which is related to entering the roadway and higher speeds of movement. In these groups, the highest frequency of severe multiple injuries is observed, requiring surgical intervention and prolonged hospitalization.

A positive correlation was established between the child's age and injury severity for electric scooters (r=0.68, p<0.01), explained by higher speeds of movement of older children. For hoverboards, this relationship was weaker (r=0.42, p<0.05) due to maximum speed limitations by the device design. Detailed distribution of injury mechanisms by age groups is presented in Table 3.

Table 3

Injury mechanisms in children of different age groups during operation of electric scooters

Age group	Fall from scooter (%)	Collision with car (%)	Traumatic brain injury (%)
4-6 years (n=18)	100	0	28
7-9 years (n=16)	98	2	45
10-13 years (n=28)	57	8	68
14-18 years (n=22)	55	12	74

Notes: n – number of children examined.

The obtained research results are consistent with international scientific literature data on the features of trauma during operation of electric personal mobility devices. The established high frequency of traumatic brain injury when using electric scooters (72 %) correlates with the study by Demir et al. (2023), who found that traumatic brain and craniomaxillofacial injuries constitute the most common type of injuries during operation of electric scooters among youth [13]. McKay et al. (2023) in their study of neurosurgical outcomes of electric scooter use also confirm the high frequency of severe traumatic brain injuries requiring neurosurgical intervention, with the authors emphasizing the critical role of speed of movement and absence of protective helmet as main risk factors [14]. Kim and Lee (2023) in a systematic review of the epidemiology of fractures in electric scooter injuries established that upper limb fractures constitute 40-45 % of all fractures, corresponding to our data on the dominance of upper limb injuries during the protective reflex during falls [15].

The identified strong inverse correlation between protective helmet use and frequency of traumatic brain injury (r=-0.71, p<0.001) is confirmed by results of the study by Cittadini et al. (2023), who demonstrated that helmet use reduces the severity of traumatic brain injury in electric scooter accidents by 52-65 % [16]. Trivedi et al. (2019) in their pioneering study of electric scooter-related injuries found an extremely low level of helmet use (4.4 %), consistent with our data on protective equipment use in only 12 % of cases [17]. Flaherty et al. (2025) established that adding an electric motor to recreational vehicles doubles the risk of serious injuries and craniofacial fractures in the pediatric population, with helmet use associated with an 87 % reduction in skull fracture risk (OR 0.13, p<0.001), confirming the critical importance of personal protective equipment [18].

The age-related features of injury mechanisms identified in our study coincide with the results of Morgan et al. (2022), who described a series of pediatric cases of electric scooter injuries in the United Kingdom and noted that 50 % of children required orthopedic surgical intervention, with no patient using a helmet at the time of injury [19]. Navarro et al. (2022) in a national study of hospitalization risk for scooter injuries established that hospitalization rates increased by 13.1 % annually, and patient age was an independent predictor of injury severity and hospitalization necessity, consistent with our identified positive correlation between age and injury severity [20]. The obtained mathematical modeling results can be used for developing scientifically based preventive strategies and improving forensic medical expert assessment of injury mechanisms in cases of accidents with electric personal mobility devices in childhood.

Conclusions. Mathematical and biomechanical models of three main mechanisms of child injury during operation of electric personal mobility devices have been developed: falling from a moving vehicle, collision with a pedestrian, and collision with an automobile. It has been established that the nature and localization of bodily injuries are determined by the type of vehicle, speed of movement, fall height, the child's anthropometric data, and presence of personal protective equipment.

For electric scooters, the most typical is forward fall with head and upper limb impact, leading to traumatic brain injury (72 % of cases), neck injuries (75 %), and upper limb fractures. For hoverboards, lateral fall with predominant upper limb injuries (48%) and significantly lower frequency of traumatic brain injury (26 %) is characteristic.

A strong inverse correlation has been revealed between protective helmet use and frequency of traumatic brain injury (r=-0.71 for electric scooters, r=-0.58 for hoverboards, p<0.01), substantiating the necessity of mandatory use of personal protective equipment.

Age-related features of injury mechanisms have been established: for children 4-6 years, exclusively falls at low speeds are characteristic, whereas in adolescents 14-18 years, the frequency of collisions with automobiles (12 %) and injury severity increases. The positive correlation between age and injury severity (r=0.68, p<0.01) is explained by higher speeds of movement of older children.

Modeling results can be used in forensic medical practice for establishing injury mechanisms, determining accident circumstances, and developing expert conclusions. The practical significance of the study also lies in the possibility of developing scientifically based preventive measures, including age restrictions, mandatory use of protective equipment, and regulation of speed of movement of electric personal mobility devices.

Study limitations and prospects for further research. The present study has certain limitations that should be acknowledged. The sample size of 84 cases, while adequate for establishing primary injury patterns and biomechanical relationships, represents a limitation for detecting more subtle differences between smaller subgroups and rare injury types. Additionally, the study was conducted within a single geographic region (Ivano-Frankivsk Oblast), which may limit the generalizability of findings to populations with different demographic characteristics, traffic infrastructure, and patterns of electric personal mobility device usage.

These limitations can be effectively addressed in future research through expansion of the study cohort and geographic scope. Multicenter collaborative studies involving multiple regions of Ukraine and international partners would significantly increase sample size, enabling more robust statistical analysis of subgroup differences and rare injury mechanisms. Geographic expansion would also allow validation of the developed biomechanical models across diverse populations, confirming their applicability in different settings and enhancing their utility for forensic medical practice nationwide and internationally.

Beyond addressing current limitations, future research directions include: development of prospective injury surveillance systems for real-time data collection; integration of advanced imaging modalities and patient-specific anatomical data to refine biomechanical models; experimental validation using pediatric anthropomorphic test devices; comprehensive evaluation of protective equipment effectiveness to inform evidence-based safety standards; and longitudinal follow-up studies to assess long-term developmental outcomes in injured children. These investigations would build upon the foundation established by the present study, advancing both forensic medical expertise and public health prevention strategies for this emerging category of pediatric trauma.

Conflict of interest: absent.

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МОДЕЛЮВАННЯ МЕХАНІЗМУ ТРАВМУВАННЯ ДІТЕЙ ПРИ ЕКСПЛУАТАЦІЇ ЕЛЕКТРИЧНИХ ЗАСОБІВ ПЕРСОНАЛЬНОЇ МОБІЛЬНОСТІ

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Резюме. Популярність електросамокатів, гіробордів та електровелосипедів серед дітей призвела до значного зростання кількості травм, що потребує детального вивчення механізмів їх утворення. Проаналізовано 84 випадки травмування осіб віком від 4 до 18 років. Характер та локалізація тілесних ушкоджень залежать від типу транспортного засобу, віку дитини, швидкості руху та наявності засобів індивідуального захисту. Для електросамокатів найбільш типовими є черепно-мозкова травма (72 %), травми шиї (75 %) та нижніх кінцівок (56 %). Для пригод за участю гіробордів найбільш характерними є травми верхніх кінцівок (48 %), що стаються внаслідок падіння через втрату рівноваги. Електровелосипеди призводять до травм грудної клітки (75 %) через вищу швидкість руху та можливість зіткнення з іншими транспортними засобами. Розроблено математичні та біомеханічні моделі з використанням рівнянь класичної механіки та методу скінченних елементів, що дозволяють прогнозувати характер травмування залежно від параметрів падіння, антропометричних даних дитини та технічних характеристик транспортного засобу. Встановлено сильний зворотний кореляційний зв’язок між використанням захисного шолома та частотою черепно-мозкової травми ($r=-0,71$ для електросамокатів, $p<0,001$). Виявлено вікові особливості механізмів травмування: для дітей 4-6 років характерні виключно падіння на низьких швидкостях, тоді як у підлітків 14-18 років зростає частота зіткнень з автомобілями (12%) і тяжкість травм. Позитивний кореляційний зв’язок між віком і тяжкістю травми ($r=0,68$, $p<0,01$) пояснюється вищими швидкостями руху старших дітей. Результати моделювання можуть бути використані у судово-медичній практиці для встановлення механізму травмування, визначення обставин нещасного випадку, розробки науково обґрунтованих превентивних заходів та удосконалення експертної оцінки механізму травмування.

Ключові слова: транспортна травма, дитячий вік, електричні засоби персональної мобільності, моделювання механізму травмування, черепно-мозкова травма, судово-медична експертиза, біомеханічне моделювання, метод скінченних елементів, засоби захисту.

Конфлікт інтересів: відсутній.

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