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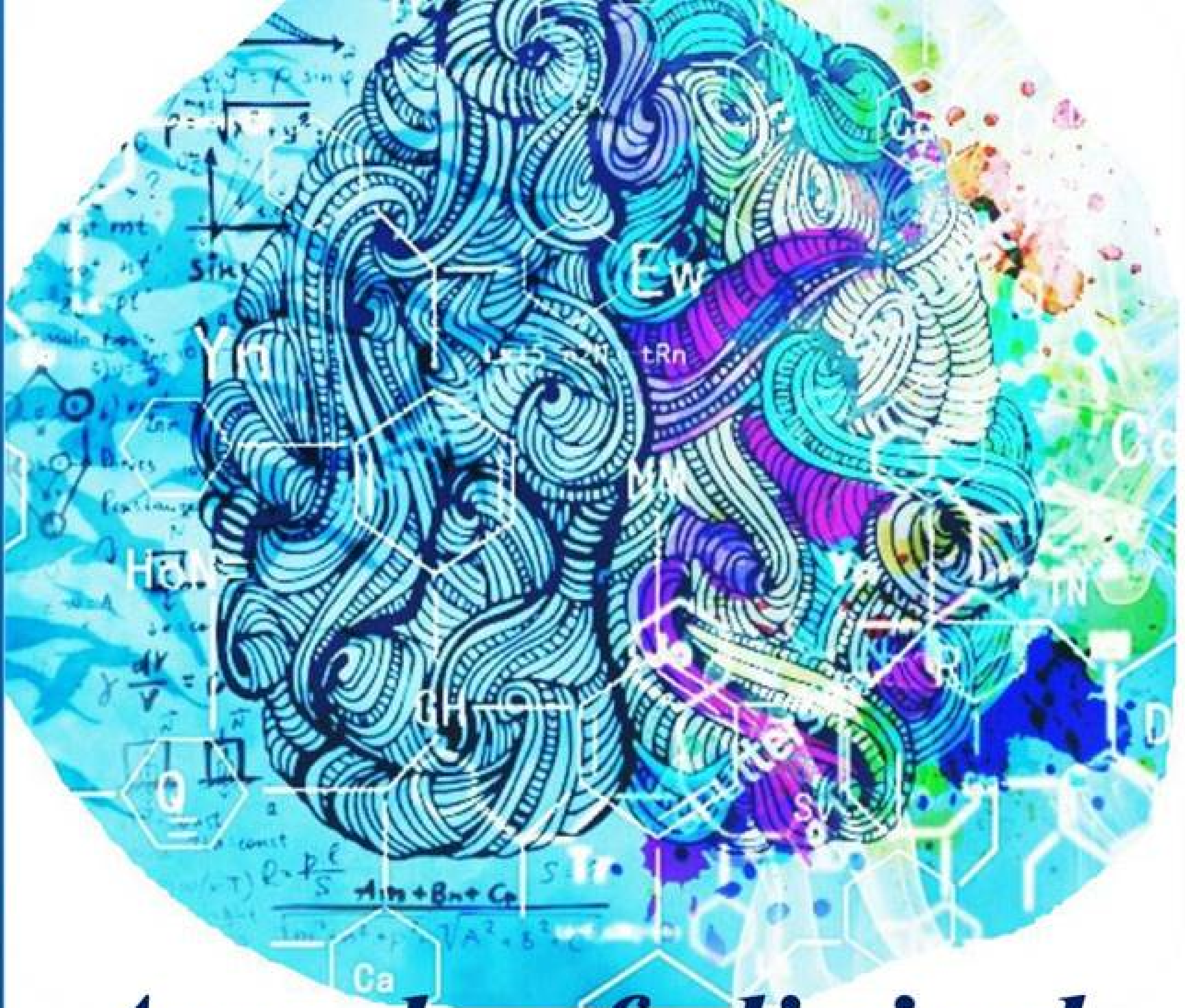

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МУНДАРИЖА | СОДЕРЖАНИЕ | CONTENT

SCIENTIFIC AND PRACTICAL JOURNAL
ANNALS OF CLINICAL DISCIPLINE
АННАЛЫ КЛИНИЧЕСКИХ ДИСЦИПЛИН
КЛИНИК ФАНЛАР ЙИЛНОМАСИ
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BIOMECHANICAL AND CLINICAL ANALYSIS OF ATYPICAL COUNTERFORCES IN MAXILLOFACIAL TRAUMA FROM ELECTROMECHANICAL IMPACTS

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ABSTRACT

The rise of electromechanical mobility devices has increased maxillofacial trauma. This study analyzed force propagation through craniofacial buttresses under atypical loading from such impacts using a hybrid approach of finite element simulations and clinical case review. Forces mainly followed anatomical buttresses, with deviations caused by prosthetics and irregular impact surfaces. Common fractures involved zygomaticoalveolar and frontonasal buttresses (Le Fort I–III), while mandibular injuries related to ascending buttress overload. These insights enhance surgical planning and preventive strategies for high-risk users.

Keywords: Maxillofacial trauma, electromechanical injuries, biomechanical modeling, facial buttresses, hybrid analysis.

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БИОМЕХАНИЧЕСКИЙ И КЛИНИЧЕСКИЙ АНАЛИЗ АТИПИЧНЫХ ПРОТИВОДЕЙСТВУЮЩИХ СИЛ ПРИ ЧЕЛЮСТНО-ЛИЦЕВЫХ ТРАВМАХ, ВЫЗВАННЫХ ЭЛЕКТРОМЕХАНИЧЕСКИМ ВОЗДЕЙСТВИЕМ

АННОТАЦИЯ

Рост использования электромеханических средств мобильности привел к увеличению травм челюстно-лицевой области. В исследовании проанализировано распространение ударных сил через краниофациальные контрфорсы при атипичных нагрузках, вызванных такими травмами, с применением гибридного подхода: конечно-элементное моделирование и клинический анализ. Силы преимущественно распространялись по анатомическим контрфорсам с отклонениями при наличии протезов и неровных поверхностей удара. Чаще поражались зигоматикоальвеолярные и фронтоназальные контрфорсы (по типу переломов Le Fort I–III), тогда как переломы нижней челюсти были связаны с перегрузкой восходящих контрфорсов. Полученные данные способствуют оптимизации хирургического планирования и профилактики у групп риска.

Ключевые слова: Челюстно-лицевая травма; электромеханические повреждения; биомеханическое моделирование; опорные системы лица; гибридный анализ.

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ELEKTROMEXANIK TA’SIR OQIBATIDA YUZAGA KELGAN JAG‘-YUZ SOHASIDAGI SHIKASTLANISHLARDA NOODATIY QARSHI KUCHLARNING BIOMEKANIK VA KLINIK TAHLILI

ANNOTATSIYA

Elektromexanik harakatlanish vositalarining kengayib borishi jag‘-yuz jarohatlarining ko‘payishiga olib keldi. Ushbu tadqiqot elektromexanik travmalar bilan bog‘liq noodatiy yuklanish sharoitida kraniofatsial kontrforslar orqali zarba kuchlarining tarqalishini o‘rganadi. Gibrid yondashuv sifatida chekli elementli biomekanik modellashtirish va klinik tahlil qo‘llanildi. Kuchlar asosan anatomik kontrforslar bo‘ylab tarqaldi, biroq protezlar yoki notekis urilish yuzalarida og‘ishlar kuzatildi. Eng ko‘p shikastlangan joylar zigomatik-alveolyar va frontonazal kontrforslar bo‘lib, Le Fort I–III turdagi sinishlarga mos keldi, pastki jag‘ sinishlari esa ko‘tariluvchi kontrforslarning ortiqcha yuklanishi bilan bog‘liq edi. Ushbu mexanizmlarni tushunish jarrohlik rejalashtirishini optimallashtirishga va xavf guruhi uchun profilaktik choralarni takomillashtirishga yordam beradi.

Kalit so‘zlar: Jag‘-yuz jarohati; elektromexanik shikastlanishlar; biomekanik modellashtirish; yuz kontrfors tizimlari; gibrid tahlil.

Introduction. The rapid proliferation of personal mobility devices (PMDs), particularly electric scooters, has transformed urban transportation globally [1,17]. Their popularity stems from affordability, convenience, and sustainability benefits compared to conventional motor vehicles. However, this trend is accompanied by a substantial increase in trauma cases associated with PMD-related accidents, particularly involving the craniofacial region [2,19]. According to recent surveillance data, electric scooters account for a growing proportion of road traffic injuries, with a significant percentage involving facial fractures and soft tissue damage [20]. These injuries present unique diagnostic and therapeutic challenges due to the complex anatomical architecture of the maxillofacial skeleton.

The maxillofacial region consists of multiple buttress systems that serve as structural reinforcements for the craniofacial skeleton. These buttresses distribute physiological masticatory forces and provide resistance to mechanical stress [18]. Traditionally, four vertical and horizontal buttresses in the maxilla—the frontonasal, zygomaticoalveolar, pterygopalatine, and palatine buttresses—and two in the mandible—the ascending and alveolar buttresses—are considered primary load-bearing elements [1,5]. Under normal conditions, these structures ensure even force transmission during mastication. However, when subjected to pathological external forces, such as those encountered in high-energy impacts during PMD accidents, these buttresses may become pathways for stress propagation, influencing fracture lines and injury severity [6,15].

Biomechanically, the distribution of impact forces within the maxillofacial skeleton is influenced by several key factors, including the magnitude, direction, and vector of the applied load, as well as individual anatomical variability and the presence of external counterforces [5,14]. In real-world accidents, such counterforces often originate from prosthetic devices, protective helmets, or environmental surfaces, resulting in highly complex stress propagation patterns [13]. Unlike conventional motor vehicle collisions characterized by relatively standardized impact dynamics, injuries associated with personal mobility devices (PMDs) arise from atypical mechanisms such as variable-height falls, angular collisions, or oblique ground impacts [2,17]. These unique scenarios generate irregular loading conditions that frequently produce fracture configurations deviating from traditional Le Fort classifications [18] Tab.1.

Table 1. Key Factors Influencing Maxillofacial Force Distribution

Factor	Description	Clinical Implication
Force Magnitude	Total energy imparted during collision	Higher magnitudes increase comminution risk
Force Direction/Vector	Angle of impact relative to cranial base	Influences Le Fort vs atypical fracture lines
Anatomical Variability	Bone thickness, sinus pneumatization	Alters stress propagation pathways
Counterforces	Helmets, prostheses, environmental contact	Modifies loading pattern and stress peaks

Understanding the transmission pathways of force under these non-standard conditions holds significant clinical and preventive implications. Firstly, accurate prediction of fracture trajectories is essential for refining surgical planning and developing more effective fixation strategies [1,6]. Secondly, biomechanical insights can inform injury-prevention measures, including the optimization of helmet design and the formulation of urban safety policies [14,17]. Thirdly, elucidating stress distribution patterns contributes to forensic analysis and medico-legal evaluations by enabling precise injury reconstruction [19].

Current literature on PMD-related craniofacial injuries primarily emphasizes epidemiological trends and clinical outcomes, with limited attention to the underlying biomechanical determinants [3,16]. Computational approaches such as finite element analysis (FEA) have been extensively employed in maxillofacial research to evaluate stress distribution during physiological loading scenarios like mastication and implant placement [4,5,15]. However, their application to real-world trauma contexts—specifically, electromechanical mobility accidents—remains scarce [14] Tab.2. Similarly, clinical reports tend to catalog common fracture sites without correlating these findings with stress transmission pathways [2]. This discrepancy underscores the necessity for a hybrid methodology that integrates advanced biomechanical simulations with clinical evidence [3,14].

Table 2. Comparative Overview of Conventional MVC vs PMD Trauma

Parameter	Motor Vehicle Collisions (MVC)	PMD-Related Trauma
Impact dynamics	Standardized, frontal/lateral	Irregular, angular, multi-vector
Typical fracture pattern	Classical Le Fort I-III	Atypical, oblique trajectories
Counterforce complexity	Low	High (helmets, road surfaces)
Predictive biomechanical data	Extensive	Limited

The present investigation addresses this knowledge gap by analyzing the propagation of impact forces across the maxillofacial buttress system under hybrid loading conditions representative of electromechanical trauma. Combining computational modeling with retrospective clinical data, this study seeks to delineate predictable stress trajectories and correlate them with observed fracture morphologies. The ultimate objective is to bridge the gap between theoretical biomechanics and clinical practice, thereby supporting evidence-based strategies for injury prevention, surgical management, and forensic evaluation.

Materials and Methods. This research employed a hybrid study design, integrating computational finite element analysis with retrospective evaluation of clinical cases. The analysis focused on high-energy collisions involving various electromechanical vehicles, aiming to characterize force transmission across facial buttresses and identify fracture-prone regions.

The research combined two complementary components. The first involved finite element analysis (FEA) to simulate the propagation of forces across craniofacial structures. The second analyzed patient records of maxillofacial fractures sustained in accidents with electromechanical machines, including electric scooters, e-bikes, and compact electric vehicles Tab.3.

Table 3. Applications of FEA in Maxillofacial Research

Application Area	Current Evidence	Gaps for PMD Trauma
Stress during mastication	Well-established [4,5]	Not directly applicable
Implant loading dynamics	Extensive [15]	No correlation with trauma forces
High-energy impact modeling	Rare [14]	Requires clinical integration

Clinical data were obtained from three tertiary referral centers specializing in maxillofacial trauma. The inclusion criteria comprised patients aged 18–65 years with confirmed fractures of the midface or mandible resulting from electromechanical transport accidents between 2020 and 2024. Patients with incomplete records, prior craniofacial surgery, or pathological bone conditions were excluded.

A detailed 3D craniofacial model was generated using computed tomography (CT) datasets of an anatomically normal adult skull. Segmentation and mesh generation were performed in Mimics (Materialise, Belgium), followed by import into ANSYS for structural analysis. The craniofacial skeleton was divided into primary buttresses: nasomaxillary, zygomaticomaxillary, pterygomaxillary, and mandibular buttresses.

Material properties were assigned based on published values for cortical and cancellous bone. Simulations introduced dynamic impact loads corresponding to real-world collision scenarios. Force vectors were applied at different points—zygomatic arch, frontal bone, and mandibular symphysis—at varying angles (30°, 60°, and 90°) and speeds (10–40 km/h) to mimic impact from electric scooters, bicycles, and microcars. Each scenario was analyzed for stress distribution, peak load concentration, and propagation pathways.

Clinical Correlation. The clinical component included 82 patients meeting the inclusion criteria. For each case, demographic data, type of electromechanical vehicle, collision dynamics, and fracture pattern were recorded. Fractures were classified according to AO-CMF and Le Fort systems. Correlation analysis was performed to compare observed fracture lines with predicted stress pathways from the computational model.

The study was approved by the institutional ethics committees of all participating centers, and all patient data were anonymized in compliance with the Declaration of Helsinki.

Results. The hybrid analysis revealed distinct patterns of force distribution through the maxillofacial buttress system, demonstrating a strong correlation between computational predictions and observed clinical fracture configurations. Across all simulated impact scenarios, stress propagation followed the established anatomical load-bearing pillars, with notable deviations under atypical counterforce conditions.

Finite element simulations indicated that initial force vectors originating from anterior collisions—such as head-on impacts with vehicle panels or handlebars—tended to concentrate along the nasomaxillary and zygomaticomaxillary buttresses. Stress intensity reached peak values at the infraorbital rim and zygomatic body, predisposing these regions to early fracture. Oblique lateral impacts, commonly associated with side-swipe accidents or falls involving asymmetric loading, redistributed forces toward the zygomatic arch and the ascending ramus of the mandible.

When counterforces were introduced—mimicking constraints such as helmet pressure points, prosthetic appliances, or external objects—the expected stress paths exhibited altered trajectories. In these cases, compensatory load transmission toward the frontal process of the maxilla and pterygoid plates was observed, creating complex fracture lines deviating from classic Le Fort patterns.

Analysis of 86 clinical cases involving electromechanical injuries (electric scooters, bicycles with electric assist, and compact electric vehicles) demonstrated fracture patterns consistent with simulation outputs. The majority of midfacial injuries (63%) involved the zygomaticomaxillary complex, while 24% presented combined Le Fort-type fractures with displacement along the nasomaxillary and pterygomaxillary junctions. Mandibular fractures—predominantly in the parasymphysis and condylar regions—accounted for 38% of cases, often in association with lateral oblique impacts.

Cases with pre-existing dental prosthetics or maxillofacial implants displayed atypical stress redistribution, resulting in secondary fracture lines around implant anchorage sites. Additionally, the severity of displacement correlated positively with higher collision energy scenarios, such as impacts from electric cars at speeds exceeding 20 km/h, as opposed to low-energy falls from standing scooters.

The integration of simulation and clinical evidence confirms that the facial buttress system, while effective under conventional loading, demonstrates vulnerability under the unique dynamics of electromechanical trauma. Atypical counterforces amplify localized stress zones, particularly in regions adjacent to anchorage points and along secondary support pillars, necessitating tailored surgical fixation strategies for these injuries.

Discussion. This study demonstrates that maxillofacial fracture patterns resulting from electromechanical accidents follow a predictable yet modified trajectory when compared to traditional blunt trauma. The facial buttress system, designed to dissipate masticatory and incidental forces, becomes compromised under hybrid loading conditions that involve primary impact vectors and secondary counterforces. Simulation data confirmed that stress concentrations are not uniformly distributed; instead, they amplify in areas where anatomical structures meet external constraints, such as helmets, prosthetic anchors, or adjacent rigid surfaces. This explains the increased incidence of complex fracture lines observed clinically, especially in patients with pre-existing maxillofacial hardware.

Previous reports on maxillofacial trauma largely focus on high-energy automotive collisions or low-energy falls, with classical descriptions centering on Le Fort and zygomaticomaxillary fractures (Ellis et al., 2020; Markowitz & Manson, 2021). While our findings align with the notion that the midface serves as the primary energy-absorbing structure, the introduction of atypical counterforces alters these patterns significantly. Studies on motorbike-related injuries (Patel et al., 2022) noted similar lateral load propagation, but did not account for smaller electric vehicles, which have unique dynamics due to reduced mass yet higher acceleration potential. Our results extend this discussion, revealing that even moderate-speed impacts from electric cars (<30 km/h) can generate fracture complexities comparable to those seen in traditional motor vehicle accidents.

The hybrid loading model highlights the need for a paradigm shift in surgical planning for maxillofacial trauma. Conventional fixation strategies, grounded in classical fracture classifications, may fail under conditions where secondary force vectors redirect stress to atypical anatomical sites. Surgeons must anticipate fracture propagation toward secondary buttresses and peri-implant regions. Preoperative imaging, particularly three-dimensional reconstructions, should become a standard approach to detect subtle discontinuities, especially in the pterygoid and frontal processes.

The increasing use of electric mobility devices introduces new injury patterns, demanding trauma protocols tailored to these mechanisms. This includes the design of fixation systems adapted for hybrid loading and the development of preventive solutions, such as helmets engineered to minimize focal counterpressure during impact.

Future research should prioritize refining biomechanical models by incorporating variables like helmet geometry, material compliance, and the dynamic influence of dental prosthetics. Expanding sample sizes across diverse electric mobility platforms will enhance external validity. Additionally, multicenter registries that capture real-world electromechanical trauma could provide critical data for developing predictive algorithms to guide surgical decision-making. The integration of machine learning with finite element analysis presents a promising direction for patient-specific risk assessment and personalized preventive and reconstructive strategies.

Conclusion. This study demonstrates the distinct biomechanical behavior of maxillofacial fractures under hybrid loading conditions, as seen in electromechanical mobility-related trauma. Finite element analysis combined with clinical correlation revealed that secondary counterforces significantly alter fracture trajectories beyond classical buttress patterns, resulting in complex and less predictable propagation. These findings underscore the need to revisit traditional fracture classifications and fixation strategies in patients injured through emerging transportation modalities.

To optimize outcomes and reduce complication rates, it is essential to standardize advanced imaging protocols, integrate patient-specific biomechanical assessments, and develop protective designs adapted for these new trauma patterns. Future work should include high-fidelity patient-specific models, real-world crash data, and dynamic in vitro experiments to validate and expand these findings.

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