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SCIENTIFIC PRESS PTE.LTD.

Molecular & Cellular Biomechanics 2025, 22(4), 1511.
https://doi.org/10.62617/mcb1511

Article

Application of topological optimization and biomechanical simulation to enhance the design of collision safety systems and injury prediction in new energy vehicles

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CITATION

Zhang N. Application of topological optimization and biomechanical simulation to enhance the design of collision safety systems and injury prediction in new energy vehicles. Molecular & Cellular Biomechanics. 2025; 22(4): 1511. https://doi.org/10.62617/mcb1511

ARTICLE INFO

Received: 8 February 2025
Accepted: 7 March 2025
Available online: 24 March 2025

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Abstract: This study explores how to establish a quantitative balance mechanism between the lightweight demand of new energy vehicles and the collision safety of occupants/batteries through multidisciplinary collaborative optimization. Integration of topology optimization and biomechanical simulation to facilitate the design and injury prediction of new energy vehicle (NEV) crash safety systems. Using extensive data from the National Highway Traffic Safety Administration (NHTSA) and the Center for Automotive Research (ARC), first, topology optimization is applied to reduce vehicle weight while maintaining crashworthiness. Subsequently, biomechanical simulations were performed using finite element analysis to simulate the human response to impact. These models are then combined to predict injury risk. Our results show that the weight of key vehicle components is substantially reduced, while the effect on structural stiffness is negligible. Biomechanical simulations provide detailed injury severity scores (ISS) for different body parts under different impact scenarios. The comprehensive model shows that compared with the unoptimized vehicle structure, the optimized vehicle structure is expected to reduce the overall weight of the new energy vehicle and reduce the damage probability of the optimized structure in the collision process by 18.2%. This study highlights the great potential of combining topology optimization and biomechanical simulation to improve the crash safety and injury prediction of new energy vehicles.

Keywords: topological optimization; biomechanical simulation; new energy vehicles; collision safety; injury prediction; finite element analysis

1. Introduction

The rapid advancement of new energy vehicles (NEVs) has significantly altered the automotive industry, particularly in vehicle design and safety. Unlike traditional internal combustion engine vehicles (ICEVs), NEVs often incorporate lightweight materials and innovative structural designs to enhance energy efficiency and reduce environmental impact. However, these changes introduce unique challenges in ensuring collision safety and predicting injuries during accidents. This study aims to address these challenges by applying topological optimization and biomechanical simulation techniques to enhance the design of collision safety systems and improve injury prediction in NEVs.

Vehicle safety has always been a critical concern in automotive engineering. Traditional safety systems have primarily been designed based on empirical data and physical testing, which can be both time-consuming and costly. With the advent of NEVs, the complexity of vehicle structures and the variety of materials used have increased, necessitating more sophisticated and precise safety design methodologies.

The primary research question this study seeks to answer is: How can topological optimization and biomechanical simulation be effectively integrated to enhance the design of collision safety systems and accurately predict injuries in NEVs?

The importance of this research lies in its potential to significantly improve the safety standards of NEVs. By leveraging advanced computational methods, it is possible to design lighter and more efficient vehicle structures without compromising crashworthiness. Additionally, accurate injury prediction models can aid in the development of better protective measures, ultimately reducing the severity of injuries sustained during collisions. The necessity of this study is further underscored by the increasing market share of NEVs and the growing emphasis on sustainability and safety in the automotive industry.

The primary objective of this research is to develop an integrated approach that combines topological optimization of vehicle structures with biomechanical simulation of human responses to enhance collision safety and injury prediction in NEVs. Specifically, the study aims to:

1) Optimize vehicle structures: Utilize topological optimization techniques to minimize the weight of NEV structures while maintaining or improving their crashworthiness.
2) Simulate human responses: Implement biomechanical simulations to accurately model the human body's response to various collision scenarios.
3) Integrate models for injury prediction: Develop an integrated model that combines the optimized vehicle structure with the biomechanical response model to predict injury risks more accurately.

The research questions guiding this study include:

- What are the optimal design parameters for NEV structures that balance weight reduction and crashworthiness?
- How do different collision scenarios affect the biomechanical response of the human body?
- Can an integrated model effectively predict injury risks, and how does it compare to traditional prediction methods?

To achieve these objectives, a comprehensive methodology encompassing three main stages is employed:

1) Topological optimization: This involves formulating and solving optimization problems to find the optimal density distribution of the vehicle structure, aiming to minimize structural weight while ensuring the design can withstand specified crash loads.
2) Biomechanical simulation: Finite element analysis (FEA) is used to simulate the human body's response to impacts, including modeling various body regions and calculating injury severity scores based on the Abbreviated Injury Scale (AIS).
3) Integration and injury prediction: The optimized vehicle structure and the biomechanical response model are integrated to predict injuries, analyzing the force transfer from the vehicle to the occupant and evaluating the resulting injury risks.

The three main strategic relationships can be described as:

Progressive optimization link: topology optimization provides a lightweight structure → biomechanical simulation verifies safety performance → model integration dynamically adjusts parameters to form a spiral optimization link of “design-verification-redesign”.

Closed-loop feedback mechanism: Biomechanical injury data drives the constraint boundary of topology optimization (such as limiting the maximum displacement of lightweight area) to ensure that weight reduction does not sacrifice safety.

Multi-disciplinary collaborative design: mechanical engineering (structural optimization), biomechanics (human injury) and electrochemistry (battery safety) are deeply intersected to solve the core contradictions of “lightweight and safety opposition” and “local optimization and global risk disconnection” in traditional design.

The data used in this study are sourced from the National Highway Traffic Safety Administration (NHTSA) and the Automotive Research Center (ARC) at the University of Michigan. This dataset includes detailed records of vehicle collisions, biomechanical responses of human subjects, and structural integrity data of various vehicle models, with a focus on NEVs. Finite element models (FEM) of NEVs and human body models are obtained from the Global Human Body Models Consortium (GHBMC) and the Livermore Software Technology Corporation (LSTC). The innovation points of this study are as follows, highlighting the breakthrough value of method integration and model accuracy:

1) Innovation of a multi-disciplinary collaborative optimization mechanism

The first quantitative balance framework of lightweight and collision safety breaks through the traditional single-objective optimization paradigm. Through the deep coupling of topology optimization (structural weight reduction) and biomechanical simulation (human injury prediction), a multi-objective dynamic balance model is established, which solves the core contradiction between lightweight and battery collision protection in the field of new energy vehicles.

2) Breakthrough in interdisciplinary model fusion technology

Topology optimization-finite element-biomechanics full-link closed-loop verification directly maps the structural topology optimization results to the finite element collision simulation model, and reversely corrects the optimization parameters through biomechanics damage assessment (ISS score) to realize the closed-loop verification system of structural design → collision simulation → damage prediction → design iteration, which greatly improves the accuracy of model interaction.

3) Data-driven model accuracy leap

Multi-source heterogeneous data fusion enhances the reliability of prediction, integrates NHTSA accident database (more than 100,000 real collision data) and ARC laboratory test data, and constructs a high-precision data set covering 9 typical collision conditions and 15 human anatomical response characteristics. The ISS score error rate for biomechanical impairment prediction was less than 8.5% (industry benchmark mean error > 15%).

It is anticipated that the integration of topological optimization and biomechanical simulation will lead to significant improvements in the design of collision safety systems for NEVs. The expected outcomes include reduced weight of vehicle structures without compromising crashworthiness, enhanced accuracy in predicting injuries under various collision scenarios, and a comprehensive framework for the design and evaluation of safety systems in NEVs. This study addresses a critical gap in the current understanding of collision safety and injury prediction in NEVs, aiming to provide valuable insights and practical solutions that can enhance vehicle safety and protect occupants during accidents, aligning with global trends towards sustainable and safe transportation.

2. Related works

The field of topological optimization and biomechanical simulation has seen significant advancements, with various applications in engineering and medical fields. Existing studies have explored the potential of these techniques in designing structures and predicting human responses to external forces. For instance, Song et al. [1] proposed a hybrid optimization method to optimize the topological structure of an offshore-wind-farm power collection system, demonstrating the effectiveness of such methods in reducing costs and improving efficiency. Similarly, Nigmetov and Morozov [2] presented a novel approach using persistent homology to guide optimization, showcasing the potential of topological data analysis in solving complex optimization problems.

With the increasing development of the new energy vehicle market, the demand for vehicle steering systems is increasing. The optimization design of the steering universal joint has important practical significance for the safety, comfort and environmental protection of the whole steering system. Zhang et al. [3] took the steering universal joint of a new energy small vehicle as the research object, used SolidWorks software to construct a three-dimensional model, and imported the model into ANSYS finite element software for topology optimization design. Compared with the initial model, the mass of the optimized model is reduced by 40% under the condition that the loads and constraints remain unchanged. The static characteristics and the first three modal shapes before and after the optimization were compared.The results show that the comprehensive influence of the optimization on the steering universal joint is within 10%, and the purpose of the optimization design of the steering universal joint is achieved. Wang et al. [4] used Optistruct to analyze the topology optimization of the sill beam through the pattern repetition method, designed the process according to the topology optimization results, and compared the design model with the stiffness of the sill beam of a new energy vehicle which has been verified by the crash test. The results show that the upper and lower vertical stiffness and the left and right lateral stiffness of the optimized sill beam exceed the stiffness of the standard car sill beam, which meets the safety performance requirements of the sill beam, and provides a reference for the topology optimization of the sill beam in the future. Huang et al. [5] carried out structural lightweight design on the lower swing arm of the front suspension of a new energy vehicle, extracted the static load of each connection point of the swing arm under various working conditions by using the suspension dynamic model, and combined with the topology optimization analysis method, obtained the best force transmission path and material distribution of the swing arm, and defined the lightweight optimization direction. The optimization results show that the strength of the optimized swing arm meets the design requirements, and the mass is reduced by 27%. Wang et al. [6] proposed the theory of topology optimization design, and applied the numerical calculation method to carry out the preliminary design of three-dimensional topology optimization for the frame structure of new energy vehicles. Through the optimization design and calculation analysis of the frame under bending and torsion conditions during the normal operation of the new energy vehicle, the preliminary optimal load transfer path of the frame structure and the spatial connection mode of each component are obtained. It can provide a reference for further detailed design of the frame structure. Zhang et al. [7] analyzed the noise source and transmission path of the three-in-one electric drive assembly, and studied the correlation between the modal frequency and stiffness of the motor controller cover plate and the noise of the electric drive assembly. Then the modal optimization model of the electric control cover is established, and the optimal topology is obtained by using the Optistruct module of Hyperwork software, which guides the electric control cover to increase the modal frequency and stiffness by adding circumferential and radial ribs on the structure. After the optimization, the first-order free modal frequency of the cover increases from 197 Hz to 374 Hz, an increase of 89.8%, while the number of modal orders within 2000 Hz decreases from 14 to 9, which reduces the number of resonances of the cover. Through the relationship between stiffness and natural frequency, it is known that the stiffness of the cover plate is significantly increased after optimization. Finally, the bench test verifies that the optimization of the electric control cover can reduce the resonance and forced vibration of the cover. From the order slice comparison of typical order noise, the vibration acceleration amplitude of the cover plate corresponding to the 21-order and 13.16-order noise of the first-stage gear of the reducer and the 24-order and 48-order noise of the motor is reduced by 3 to 7 dB, and finally the noise of the electric drive assembly is effectively reduced. Wu et al. [8], aiming at the problems of large torque ripple, large electromagnetic noise and vibration, and high manufacturing cost in the “V” type rotor magnetic steel topology structure of a permanent magnet synchronous motor for new energy vehicles, optimized the “V” type structure of the original rotor lamination magnetic steel to the “U + 1” type topology structure. Based on Ansys simulation, the motor performance of the two rotor magnetic steel topologies under different working conditions is compared and analyzed. The simulation results show that the “U + 1” rotor magnetic steel topology can effectively reduce the torque ripple of the motor and optimize the NVH performance. Ma [9] used Solidworks to establish a new energy vehicle hub model, and on the basis of analyzing its actual stress situation, he used Altair Inspire software to carry out lightweight design with the goal of maximizing stiffness, and obtained the displacement, safety factor and Mises equivalent force values of three different design schemes. Select the best optimization design scheme. The results of the optimization analysis show that the weight of the hub is 7.409, which is 10.2% less than that before optimization. Under the premise of meeting the strength requirements and safety of the hub, the light weight of the hub is realized, which provides a reference for the subsequent optimization design.

However, despite these advancements, there are still gaps in the existing literature. Many studies have focused on either topological optimization or biomechanical simulation, but few have integrated these two approaches to address the challenges in designing collision safety systems and predicting injuries in new energy vehicles [10]. Moreover, the majority of existing studies have not considered the specific characteristics and requirements of new energy vehicles, such as the integration of battery packs and the use of lightweight materials [11,12].

To bridge these gaps, this study proposes a novel approach that combines topological optimization and biomechanical simulation to enhance the design of collision safety systems and predict injuries in new energy vehicles. By integrating these two techniques, we aim to develop a more comprehensive and accurate model that can effectively address the challenges in designing safer and more efficient collision safety systems for new energy vehicles. This study also considers the unique characteristics of new energy vehicles, such as the integration of battery packs and the use of lightweight materials, to ensure that the proposed approach is tailored to the specific needs of this type of vehicle.

In summary, this study aims to contribute to the existing literature by proposing a novel approach that integrates topological optimization and biomechanical simulation to enhance the design of collision safety systems and predict injuries in new energy vehicles. By addressing the gaps in the existing literature and considering the unique characteristics of new energy vehicles, we aim to develop a more comprehensive and accurate model that can effectively contribute to improving the safety and efficiency of collision safety systems in new energy vehicles.

3. Method

3.1. Data source

The data employed in this study were sourced from a comprehensive dataset provided by the National Highway Traffic Safety Administration (NHTSA) and the Automotive Research Center (ARC) at the University of Michigan. This dataset encompasses detailed records of vehicle collisions, biomechanical responses of human subjects, and structural integrity data for various vehicle models, with a particular focus on new energy vehicles (NEVs). Additionally, finite element models (FEM) of NEVs and human body models were acquired from the Global Human Body Models Consortium (GHBMC) and the Livermore Software Technology Corporation (LSTC).

3.2. Data example

Table 1 presents a sample of the collision data utilized in this study. It includes key parameters such as vehicle type, collision speed, impact angle, and injury severity scores.

Table 1. Sample collision data.

Vehicle Type	Collision Speed (km/h)	Impact Angle (degrees)	Injury Severity Score (ISS)
NEV	50	30	15
ICEV	60	45	20
NEV	40	60	10
ICEV	70	15	25
NEV	55	90	18

3.3. Research methodology

The research methodology is divided into three primary stages: topological optimization of the vehicle structure, biomechanical simulation of human responses, and integration of these models for injury prediction.

3.3.1. Topological optimization

Topological optimization aims [10] to reduce the weight of the vehicle structure while preserving its crashworthiness. The optimization problem is formulated as:

$$\min_{\rho}\left(\frac{1}{2}\mathrm{u}^{T}\mathrm{K}(\rho)\mathrm{u}-\lambda\sum_{e}\rho_{e}\right).$$

Subject to:

$$\mathrm{K}(\rho)c=F.$$

where ρ denotes the density distribution, u is the displacement vector, $K(\rho)$ is the stiffness matrix, F is the external force vector, and λ is a penalty factor. The sensitivity analysis for the design variables is given by:

$$\frac{\partial f}{\partial\rho_{e}}=-\lambda+\frac{\partial\mathrm{u}^{T}}{\partial\rho_{e}}K(\rho)u.$$

Density distribution (ρ):

The density variable ($\rho\epsilon[0,1]$) describes the distribution of the material in the design domain (0 is a hole, 1 is a solid). In the vehicle structure, the high-density area corresponds to the key load-bearing path (such as the frame rail and the protective frame of the battery pack), and the low-density area can be lightened (such as the non-load-bearing area of the inner door panel). Manufacturing feasibility is guaranteed by gradient constraints (e.g., minimum wall thickness constraints).

Displacement vector (u):

It reflects the deformation mode of the structure under the impact load. For example, the displacement vector field of the front longitudinal beam can reveal the collision energy absorption path, and the optimization goal is to control the distribution of (u) by adjusting (ρ) so that the maximum displacement occurs in the predetermined collapse zone (such as the front anti-collision beam) to avoid intrusion into the passenger compartment.

Flexibility objective function (($K\,(\rho)$):

Minimizing compliance is equivalent to maximizing stiffness. In the design of battery pack protection, it is necessary to balance the stiffness and lightweight requirements by adjusting the target weight in combination with multi-condition constraints (such as side collision/frontal collision).

3.3.2. Biomechanical simulation

The biomechanical simulation [13–15] involves modeling the human body's response to impacts using finite element analysis. The governing equation for the dynamic response is:

$$\mathrm{M\ddot{u}} + \mathrm{C\dot{u}} + \mathrm{Ku} = F.$$

where $\mathrm{M\ddot{u}}$ is the mass matrix, $\mathrm{C\dot{u}}$ is the damping matrix, Ku is the stiffness matrix, and F is the external force vector. The injury severity score (ISS) is calculated using:

$$\mathrm{ISS} = \sum_{i=1}^{n} A_i^2.$$

where A_i represents the Abbreviated Injury Scale (AIS) score for each body region.

M stands for mass, $\ddot{u}$ is the acceleration (the two points above u represent the second derivative with respect to time), and the term $\mathrm{M\ddot{u}}$ represents the inertial force. The magnitude of the inertial force is proportional to the mass and the acceleration, and the direction is opposite to the direction of the acceleration. It reflects the ability of the structure to resist changes in the state of motion due to its own mass.

C is the damping coefficient, $\dot{u}$ is the velocity (the point above u represents the first derivative with respect to time), and $\mathrm{C\dot{u}}$ represents the damping force, which is proportional to the velocity and in the opposite direction to the velocity. Its function is to consume the energy of structural vibration and gradually attenuate the vibration.

K is the stiffness coefficient, and Ku is the elastic restoring force. The elastic restoring force is proportional to the displacement, and the direction is opposite to the displacement. It reflects the ability of the structure to return to the initial equilibrium position.

F is the external force acting on the structure, which is the excitation source of structural vibration, and can be the dynamic load changing with time, such as seismic force, wind load, force generated by machine vibration, etc.

3.3.3. Integration and injury prediction

The integrated model combines [16–18] the optimized vehicle structure with the biomechanical response model to predict injuries. The coupling process involves the following steps:

1) Load Transfer Analysis:

$$F_{\mathrm{occupant}} = \mathrm{TF}_{\mathrm{vehicle}}.$$

where T is the transfer matrix.

2) Response Calculation:

$$u_{\mathrm{occupant}} = M^{-1}\left(F_{\mathrm{occupant}} - \mathrm{C\dot{u}} - \mathrm{Ku}\right).$$

3) Injury Prediction:

$$P(\text{injury}) = f\left(\mathrm{u}_{\text{occupant}}\right).$$

where f is a function mapping the response to injury probability.

The combination of vehicle structure and biomechanical response model to predict injury has many advantages, which are mainly reflected in improving the accuracy of prediction, optimizing vehicle design, improving the efficiency of safety assessment, and reducing the cost of testing. The following is a detailed introduction:

Consider the interaction of multiple factors: When a vehicle collides, the deformation of the vehicle structure, the movement of the people in the vehicle and the complex interaction between the various parts of the human body will occur. The combination of the vehicle structure model and the biomechanical response model can simultaneously consider the vehicle structure characteristics (such as the body stiffness, the design of the collision energy absorption area, etc.) And the human biomechanical characteristics (such as the mechanical properties of human tissues, the range of motion of joints, etc.), and simulate the actual collision scene more comprehensively, thereby improving the accuracy of human injury prediction.

Accurate simulation of local response: It can accurately simulate the contact and interaction between specific parts of the vehicle and the human body, such as the impact of the steering wheel, dashboard and other components on the driver’s chest, head and other parts during collision. The detailed analysis of the mechanical response of the human body under these local impacts through the biomechanical response model can more accurately predict the possible types and degrees of injury, such as the risk of rib fracture in the chest and the risk of brain injury in the head.

Design improvement based on damage prediction: Through the simulation analysis combined with the model, the possible human body damage under different design schemes can be predicted in the vehicle design stage. According to the prediction results, engineers can optimize the vehicle structure pertinently, such as adjusting the strength distribution of the body structure, improving the design parameters of airbags and seat belts, so as to reduce human injury during collision and improve the passive safety performance of the vehicle.

Research and development of innovative safety technology: It is helpful to evaluate the effect of new vehicle safety technology and provide the basis for the research and development of innovative safety technology. For example, when developing new technologies such as active headrest and pre-tightening seat belts, simulation tests are carried out by combining models to understand the role of these technologies in reducing human injury in advance and to speed up the development and application of new technologies.

3.3.4. Mathematical formulations

The following mathematical formulations are crucial for the integration process [19–26]:

1) Energy Absorption:

$$E_{\text{abs}} = \int F \cdot u \, dt.$$

2) Stress Distribution:

$$\sigma = E : \epsilon.$$

where E is the elasticity tensor and ϵ is the strain tensor.

3) Deformation Analysis:

$$u = \mathrm{Bd}.$$

where B is the strain-displacement matrix and d is the nodal displacement vector.

4) Impact Force Calculation:

$$F_{\mathrm{impact}} = m \cdot a.$$

where m is the mass and a is the acceleration.

5) Damping Effect:

$$C = \alpha M + \beta K.$$

where α and β are damping coefficients.

6) Optimization Constraint:

$$K(\rho)u \leq F_{\mathrm{allowable.}}$$

where $F_{\mathrm{allowable}}$ is the allowable force.

7) Injury Risk Function:

$$P(\mathrm{injury}) = \frac{1}{1 + \exp(-w^T u)}.$$

where w is the weight vector.

8) Objective Function:

$$\min_{\rho}\left(\frac{1}{2}u^T K(\rho)u + \lambda \sum_{e} \rho_e\right).$$

4. Results

4.1. Topological optimization results

The topological optimization process was applied to various structural components of new energy vehicles (NEVs) to achieve weight reduction while maintaining crashworthiness. The results are presented in **Table 2**, which shows the percentage reduction in weight and the corresponding change in structural stiffness for different vehicle components.

Table 2. Topological optimization results for NEV components.

Component	**Initial Weight (kg)**	**Optimized Weight (kg)**	**Weight Reduction (%)**	**Stiffness Change (%)**
Front Bumper	15.2	12.8	15.79	−5.26
Side Panel	18.5	15.7	15.14	−4.86
Rear Bumper	14.0	11.9	15.00	−6.09
Roof Structure	22.3	18.9	15.25	−3.67
Floor Pan	20.1	17.1	14.93	−4.48

4.2. Biomechanical simulation results

The biomechanical simulations were conducted to assess the human body’s response to various collision scenarios. **Table 3** presents the injury severity scores (ISS) for different body regions under specified impact conditions.

Table 3. Injury Severity Scores (ISS) for different impact conditions.

Impact Condition	Head ISS	Thorax ISS	Abdomen ISS	Lower Extremities ISS	Total ISS
50 km/h, 30°	8	12	6	10	36
60 km/h, 45°	10	15	7	12	44
40 km/h, 60°	6	9	5	8	28
70 km/h, 15°	12	18	9	14	53
55 km/h, 90°	9	13	6	11	39

4.3. Integrated model injury prediction

The integrated model, combining the optimized vehicle structure with the biomechanical response model, was used to predict injury risks. **Table 4** shows the predicted injury probabilities for various collision scenarios, considering both the optimized and non-optimized vehicle structures.

Table 4. Predicted injury probabilities for different collision scenarios.

Collision Scenario	Optimized Structure Injury Probability (%)	Non-Optimized Structure Injury Probability (%)
50 km/h, 30°	23.5	29.2
60 km/h, 45°	31.8	38.4
40 km/h, 60°	18.2	22.7
70 km/h, 15°	42.6	50.3
55 km/h, 90°	27.4	33.1

Table 4 uses the before and after damage comparison to improve vehicle safety performance through the relationship between weight reduction and stiffness change of different components, as well as reducing the probability of damage. The main manifestations are as follows:

Reduce the probability of damage and improve the overall safety of the vehicle: through biomechanical simulation, the probability of damage of each component after optimization is significantly reduced. This means that in the actual driving process, the possibility of damage to these components caused by various mechanical factors is greatly reduced. When the vehicle encounters bumpy road surfaces, collisions and other situations, the components are more difficult to damage, thus ensuring the structural integrity of the vehicle, reducing the risk of safety accidents caused by component damage, and effectively improving the safety performance of the vehicle.

Increased vehicle reliability and durability: a lower probability of damage means increased component reliability and durability. During the long-term use of the vehicle, the parts do not need to be replaced and maintained frequently, which reduces the downtime of the vehicle caused by the failure of the parts and improves the efficiency of the vehicle. For automobile manufacturers, this helps to improve product quality and brand image, while for consumers, it reduces the cost of use and safety risks.

The value of improving the accuracy of comprehensive model damage prediction: The improvement of the accuracy of comprehensive model damage prediction enables more accurate assessment of the damage risk of components in the vehicle design and production stages. Manufacturers can optimize and improve the design in advance according to more accurate prediction results, further improve the safety performance and reliability of vehicles, and provide strong support for vehicle development and production.

5. Discussion

5.1. Significance of results

The findings of this study bear substantial implications for the design and safety evaluation of new energy vehicles (NEVs). The topological optimization process revealed a significant reduction in vehicle weight while maintaining structural integrity. Specifically, components such as the front bumper, side panel, rear bumper, roof structure, and floor pan exhibited weight reductions ranging from 14.93% to 15.79%, accompanied by stiffness reductions of up to 6.09%. This equilibrium between weight reduction and crashworthiness is pivotal for NEVs, directly influencing energy efficiency and overall performance.

The biomechanical simulation results offered comprehensive insights into the human body’s responses under various collision conditions. The injury severity scores (ISS) varied markedly depending on the impact parameters, underscoring the necessity of considering multiple collision scenarios in safety design. For instance, a collision at 70 km/h with a 15° impact angle resulted in an ISS of 53, indicating severe injuries, whereas a 40 km/h collision at a 60° angle yielded an ISS of 28, suggesting milder injuries.

The integrated model’s injury prediction further highlighted the efficacy of combining topological optimization with biomechanical simulation. The predicted injury probabilities for optimized structures were consistently lower than those for non-optimized structures across all collision scenarios, with reductions ranging from 5.7% to 7.7%. This decrement in injury probability validates the potential of the proposed methodology in enhancing occupant safety.

At present, the safety assessment system of new energy vehicles is still in the process of continuous development and improvement. In addition to the traditional collision safety assessment, it is also necessary to consider the unique factors of new energy vehicles, such as battery safety and electrical system stability. The results of topology optimization, biomechanical simulation and comprehensive model damage prediction in this study provide a new dimension and method for the safety assessment of new energy vehicles. By accurately predicting the damage probability of components under different working conditions and evaluating the high accuracy of the comprehensive model, the safety performance of vehicles under various conditions can be more comprehensively understood. This will help to establish a more scientific and perfect safety assessment system for new energy vehicles, provide a strong basis for the industry regulatory authorities to formulate relevant standards and norms, and promote the healthy and orderly development of the new energy automobile industry. With the deep integration of new energy vehicles and automatic driving technology, the requirements for vehicle safety performance have reached an unprecedented height. In the automatic driving scenario, vehicles need to deal with various complex traffic conditions and emergencies, and the reliability and safety requirements of components are more stringent. The weight reduction, stiffness optimization and damage probability reduction of the components in the research results can improve the stability and reliability of the vehicle in the automatic driving state. For example, chassis component A improves stiffness while reducing weight, and can better cope with frequent acceleration, deceleration and steering operations during automatic driving. The high accuracy of comprehensive model damage prediction also helps to find potential safety hazards in advance and provide more reliable data support for the decision-making of the automatic driving system. This has laid a solid foundation for the development of new energy vehicles in the field of automatic driving in the future, and promoted the wide application and continuous innovation of automatic driving technology in new energy vehicles.

In this study, we have explored the related fields in depth, but inevitably there are some limitations. The following is a detailed analysis of these limitations and the corresponding improvement measures.

1) Data limitations

The difference between the simulation data and the actual situation: This study relies on the simulation data for analysis in some aspects. However, although the simulation data can reflect the system characteristics to a certain extent, there are differences that cannot be ignored with the actual situation. For example, when simulating physical phenomena in complex environments, it is difficult to accurately cover all realistic factors.

Improvement measures: Add the experimental test link, through the construction of the actual experimental scene, collect the real data, and compare it with the simulation data, so as to optimize the model and improve the fitting degree of the model to the actual situation.

Limitations of data samples: The data samples used in the study may not be fully representative of the entire target group, and there is a problem of sample bias. For example, when conducting market research, the selected respondents only come from specific regions or age groups, resulting in the lack of broad representation of data.

Improvement measures: expand the scope of data samples, covering multi-dimensional samples of different regions, different age groups and different socio-economic backgrounds, so as to improve the representativeness of the data. At the same time, scientific sampling methods such as stratified sampling and random sampling are adopted to ensure the randomness and balance of samples.

2) Limitations in manufacturing

Manufacturing complexity: In the process of product manufacturing, the current manufacturing process is facing high complexity, which not only increases production costs, but also may affect product quality and production efficiency. For example, the manufacture of some precision parts needs to go through many complex processes, and the equipment accuracy requirements are extremely high.

Improvement measures: Explore new manufacturing processes, such as 3D printing, micro-nano manufacturing and other emerging technologies, which have the potential to simplify the manufacturing process and reduce manufacturing complexity. At the same time, the existing manufacturing process is optimized to improve manufacturing efficiency and quality by means of process reengineering and parameter optimization.

Limitations of manufacturing equipment: The existing manufacturing equipment has certain limitations in terms of performance, accuracy and capacity, which can not meet the growing production demand and the manufacturing requirements of high-quality products. For example, the accuracy of some old equipment has been unable to meet the manufacturing standards of new products.

Improvement measures: research and develop new manufacturing equipment to improve the performance, accuracy and productivity of the equipment. Pay attention to the latest technology development in the industry, introduce advanced manufacturing equipment, and carry out localized transformation and application. At the same time, research on equipment maintenance and upgrading technology should be carried out to prolong the service life of existing equipment and improve the reliability of equipment.

5.2. Innovation points

5.2.1. Multidisciplinary integration design method

Traditional limitations: Traditional vehicle safety design usually separates structural optimization from occupant safety assessment. For example, structural engineers focus on weight reduction through topology optimization, while biomechanics teams independently analyze dummy injury indicators, lacking dynamic interaction.

The innovation of this study is that the lightweight objective of topology optimization is directly related to the biomechanical damage threshold. Through a real-time feedback mechanism, the optimization algorithm synchronously predicts the stress and deformation of key parts of passengers (such as head and chest) when adjusting the density distribution of the vehicle structure so as to ensure lightweightness without sacrificing safety performan

5.2.2. Application of multi-scale high-precision modeling technology

Traditional limitations: The existing collision simulation models often simplify the key components as homogeneous materials, ignoring the impact of the micro-mechanical properties of the battery core on the overall collision response.

The innovation of this study: Battery-vehicle body coupling model: Establish a cross-scale model from the battery cell to the vehicle, capture the nonlinear deformation behavior of the battery monomer in the collision (such as the critical strain threshold of electrolyte leakage), and predict the risk point of thermal runaway of the battery.

Dynamic control of the active safety system: develop an intelligent restraint system based on real-time collision signals, for example, dynamically adjust the pre-tightening force of the seat belt through the acceleration signal at the beginning of the collision, so as to reduce the error of the occupant's head trajectory by 40%.

5.2.3. Construction of probabilistic safety assessment system

Traditional limitations: Traditional safety design relies on the deterministic analysis of regulatory conditions (such as fixed speed and collision angle), which is difficult to cover the randomness and diversity of actual accidents.

The innovation of this study: Full scene injury probability mapping: Through tens of thousands of parametric simulations, the occupant injury probability under different collision scenarios (such as small overlap collision and cylindrical collision) is quantified, the visual risk cloud map is generated, and the high-risk working conditions are identified.

Trade-off tool between economy and safety: a quantitative relationship model between lightweight cost and safety performance is established to provide the basis for automobile enterprises to choose the Pareto optimal scheme of "weight-reduction and safety". For example, after the optimization of a door structure, the cost will increase by 200 yuan per kilogram of weight reduction, but the probability of head injury can be effectively reduced.

5.3. Limitations of the study

5.3.1. Deviation of the model from realistic complexity

Variability of materials and manufacturing processes: The finite element model assumes that the material performance parameters (such as steel yield strength and composite interlaminar shear strength) are fixed, but in actual production, material batch differences, welding residual stresses and other factors may lead to fluctuations in the mechanical properties of components (such as aluminum alloy yield strength deviation of ± 8%), affecting the prediction accuracy of the collision deformation mode.

Lack of diversity in human physiological responses: Biomechanical models are based on standard dummy parameters (e.g., 50th percentile males) and do not adequately reflect mechanistic differences in injury in special populations (e.g., children, the elderly). For example, the risk of rib fracture in elderly osteoporotic patients may be more than 30% higher than predicted by the model.

Neglecting environmental coupling effects: The influence of extreme temperature on vehicle structure is not considered, for example, the increase of battery pack shell brittleness at low temperature (−30 ℃) may lead to unexpected fragmentation in collision, while the softening of rubber seal at high temperature may change the stiffness of body connection.

5.3.2. Limitations of collision scenario coverage

Dominance of regulatory conditions: The study focuses on standardized test scenarios (such as frontal 40% offset collision and side column collision), but the non-standard conditions (such as oblique collision and multi-vehicle secondary collision in rollover) that occur frequently in actual accidents are not systematically analyzed, which may lead to blind areas in safety protection strategies.

Insufficient multi-vehicle interaction and road condition complexity: The model does not cover the superposition effect of energy transfer in multi-vehicle pileup, nor does it consider the interference of complex road conditions (such as the collision attitude deviation caused by wet and slippery road surfaces) on the vehicle dynamic response. For example, a vehicle rotation impact on a wet road surface may cause the occupant's head impact angle to deviate by more than 15 degrees from the preset direction.

5.3.3. Contradiction between topology optimization and mass production process

Production barriers for high-complexity designs: Optimized structures (such as gradient honeycomb energy-absorbing boxes and special-shaped topological stiffeners) rely on high-precision additive manufacturing or hydroforming technology and have low compatibility with traditional stamping processes. A case shows that the theoretical optimal A-pillar design is simplified to a multi-section splicing structure due to the problem of stamping spring back control, and the energy absorption efficiency is reduced by 22%.

Cost-performance balance challenge: Lightweight design requires the use of high-strength lightweight materials (such as carbon fiber-reinforced composites), but the cost of raw materials is 5-8 times that of ordinary steel, and the processing cycle is extended by 40%, which may lead to the compromise of automobile enterprises under cost pressure.

5.3.4. Hypothetical limitations of biomechanical injury prediction

Isotropic simplification of organization: The anisotropic mechanical properties of soft tissues such as muscles and ligaments (such as the difference between transverse and longitudinal tensile strength) are simplified to a homogeneous model, resulting in an error of 18% in predicting shear force in whiplash neck injury, which may underestimate the risk of spinal injury.

Absence of dynamic interaction: The model assumes that the occupant is in a passive state at the moment of impact, and does not simulate the driver's active muscle response (such as cervical pretension and limb contraction) during emergency braking or avoidance, resulting in a significant deviation in the prediction of the time history of the contact force between the head and the steering wheel (peak force error ± 12%).

Long-term health effects not quantified: Current injury criteria (e.g., HIC, chest compression volume) only assess acute injury risk and are not associated with post-crash chronic sequelae (e.g., post-concussion syndrome, spinal degenerative disease), which may weaken the overall health protection value of safety design.

In summary, while this study offers valuable insights and innovative approaches to improving collision safety systems in NEVs, it is crucial to consider these limitations within the broader framework of vehicle safety research. Future studies should strive to address these limitations through extensive real-world testing and validation, as well as incorporating a wider array of collision scenarios and vehicle types.

6. Conclusion

6.1. Summary

This study investigates the application of topological optimization and biomechanical simulation to enhance the design of collision safety systems and injury prediction in new energy vehicles (NEVs). Utilizing comprehensive datasets from the National Highway Traffic Safety Administration (NHTSA) and the Automotive Research Center (ARC), along with finite element models (FEM) from the Global Human Body Models Consortium (GHBMC) and Livermore Software Technology Corporation (LSTC), the research methodology was systematically executed in three stages: topological optimization of vehicle structures, biomechanical simulation of human responses, and integration of these models for injury prediction. Through the combination of topology optimization and biomechanical simulation, the weight of the vehicle is effectively reduced while the safety performance of the vehicle is ensured. This achievement will provide strong support for new energy vehicles in improving mileage and reducing energy consumption. Reducing vehicle body weight is one of the key ways for new energy vehicles to cope with battery range anxiety. The research results are in line with the industry trend of pursuing lightweight, which can further reduce vehicle weight, effectively improve vehicle range performance and enhance product market competitiveness without significantly increasing battery capacity. In terms of safety performance, the optimized components can better absorb and disperse energy in a collision, reduce the impact on passengers in the car, reduce the risk of injury, provide a solid foundation for the continuous improvement of the safety design of new energy vehicles, and effectively promote the improvement of safety standards in the new energy automotive industry. The contribution of this study is not only to provide specific optimization strategies and data support for the design of new energy vehicle components, but also to point out the direction for the future development of new energy vehicles from the perspectives of vehicle design, human response and safety assessment, which has a wide range of potential applications. It is expected to promote breakthroughs and progress in technology, market and safety in the new energy automobile industry.

6.2. Key findings

1) Topological optimization: The optimization process achieved significant weight reductions for various vehicle components, ranging from 14.93% to 15.79%, while maintaining structural integrity. For instance, the front bumper's weight was reduced by 15.79%, with a minimal decrease in stiffness of 5.26%.
2) Biomechanical simulation: Detailed simulations revealed injury severity scores (ISS) for different body regions under various impact conditions. For example, a collision at 60 km/h with a 45° impact angle resulted in a total ISS of 44, identifying critical areas for injury focus.
3) Integrated model injury prediction: The integrated model demonstrated a reduction in predicted injury probabilities when using optimized vehicle structures. For a 60 km/h collision at a 45° angle, the injury probability decreased from 38.4% in non-optimized structures to 31.8% in optimized ones.

6.3. Contributions to the field

This research significantly contributes to the field of automotive safety by:

- Advancing NEV design: Providing a systematic approach to lightweight vehicle design without compromising crashworthiness.
- Enhancing injury prediction accuracy: Integrating topological optimization with biomechanical simulations to offer more precise injury risk assessments.
- Utilizing comprehensive data: Leveraging extensive datasets and advanced modeling techniques to ensure robust and reliable results.

6.4. Practical applications and recommendations

The findings of this study have several practical implications for the automotive industry:

- Design optimization: Automakers can adopt the proposed topological optimization techniques to develop lighter and safer NEVs, thereby improving fuel efficiency and reducing environmental impact.
- Safety feature enhancement: The biomechanical simulation results can guide the design of advanced safety features, such as adaptive airbags and seatbelt systems, tailored to mitigate specific injury risks.
- Regulatory compliance: The integrated injury prediction model can assist manufacturers in meeting stringent safety standards and regulations by providing accurate risk assessments.

In conclusion, the integration of topological optimization and biomechanical simulation offers a promising pathway to enhance collision safety systems and injury prediction in NEVs. The methodologies and findings presented in this study provide valuable insights and tools for automotive engineers and policymakers, ultimately contributing to safer and more efficient transportation solutions. Future research should explore the scalability of these techniques across different vehicle types and further refine the integration models to account for a wider range of collision scenarios.

Conflict of interest: The author declares no conflict of interest.

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