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Optimization Study on Folding Bicycle Frame Based on SolidWorks 2024

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Abstract:
With the acceleration of global urbanization, issues such as traffic congestion and carbon emissions have become increasingly severe. Consequently, folding bicycles have emerged as a major commuting option for urban residents. Nevertheless, the performance of many folding bicycles remains unsatisfactory. This study utilizes SolidWorks 2024 software to conduct 3D modeling, assembly, and mechanical analysis of folding bicycle frames. A 3D model (encompassing the top tube, down tube, main tube, front and rear forks, etc.) was constructed, and the Simulation module was employed to perform mechanical analysis on the frame made of 2014-T6 aluminum alloy. The optimal design was implemented by integrating principles of materials science and fluid mechanics. The research achieves frame performance enhancement from three aspects: Firstly, hollow design and thinner tubes are adopted in non-critical stress-bearing parts, while the structure and load-bearing capacity of high-stress parts are strengthened (reducing weight by approximately 35%); Secondly, the frame section is designed to be streamlined (minimizing the drag coefficient and windward area) to improve riding efficiency. Thus, the folding reliability and riding performance are optimized, and prospects for future performance improvement and material optimization (such as the application of carbon fiber materials and dynamic fatigue mechanical analysis) are proposed.

Keywords: Folding Bicycle Frame; 3D Modeling; Assembly Design; Mechanical Analysis.

1. Introduction

As urbanization advances, transportation has gradually become a critical challenge for city residents. Statistics show that by the end of 2014, China's urbanization rate had already reached 54% and is expected to rise to 70%–75% by 2050. Such rapid urbanization will inevitably exacerbate problems related to population, resources, and the environment. On the other hand, the development of a low-carbon economy has become mainstream, making energy conservation and emission reduction imperative,

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while the contradiction between urban transportation supply and demand continues to intensify [1]. Furthermore, issues such as peak-hour congestion, limited parking spaces for private cars, and worsening carbon emission pollution have significantly reduced residents' travel efficiency and quality of life. At this juncture, folding bicycles stand out due to their unique advantages: in addition to folding down to half the volume of traditional bicycles (enabling easy transport on subways, buses, and even into workplaces), they are also affordable with low maintenance costs. Consequently, folding bicycles, with their portability and adaptability, have become a popular choice, serving as a crucial means to alleviate urban pressure and practice green travel concepts, and their market demand continues to grow. According to 2015 statistics from the National Bureau of Statistics on 415 large-scale electric bicycle manufacturers, the total output of electric bicycles reached 35.51 million units, among which folding electric bicycles accounted for approximately 7.5 million units. The cumulative main business income of electric bicycle enterprises reached 81.13 billion yuan, and the annual export of electric bicycles exceeded 1 million units for the first time, with 900,000 units exported to Asia [2]. However, existing products rarely balance foldability and stiffness, and many suffer from insufficient riding comfort. Currently, common folding bicycles on the market can be categorized by their folding methods as follows: Frame Girder Folding Bicycles: These offer strong load-bearing capacity but have an irregular folded shape. When the wheels are inoperable, they can only be carried rather than pushed, making them inconvenient to transport. Front and Rear Fork Folding Bicycles: These can be pushed when folded, but their unique folding mechanism results in lower load-bearing capacity compared to frame girder folding bicycles. Seat Tube Frame Folding Bicycles: These primarily fold the seat tube and front frame, featuring a simpler folding process but failing to address the issue of low load-bearing capacity [3]. Therefore, conducting modeling research using SolidWorks 2024 can reduce costs. Prior mechanical analysis and material selection based on 3D models play a key role in enhancing the comprehensive performance of folding bicycles. The main methodology of this study involves 3D modeling first, followed by assembly, and finally using the Simulation module for material selection and mechanical analysis.

2. Research subjects and analysis

2.1 Basic Principles

The design of folding bicycles incorporates interdisciplinary knowledge, including mechanics, materials science, and fluid mechanics. These intertwined principles collectively determine the performance and structural strength of folding bicycles.

2.1.1 Material Perspective Analysis

In materials science, aluminum alloy is widely adopted as the mainstream material for folding bicycle frames due to its favorable strength properties. This study primarily uses 2014-T6 aluminum alloy for frame manufacturing. After specific treatment, this alloy achieves a yield strength of approximately 470 MPa and a density of around 2.8 g/cm^3, which not only meets the strength requirements for daily riding but also effectively reduces the overall vehicle weight to enhance portability. It also possesses the following advantages: 1. Lightweight Advantage: The specific gravity of aluminum is roughly one-third that of steel, enabling aluminum alloy to significantly reduce the vehicle's self-weight. Notably, bicycle speed is inversely proportional to its weight—every 10% reduction in weight improves human-powered efficiency by 7%. To boost riding efficiency, reducing the bicycle's overall weight is crucial. Although the elastic modulus of aluminum (69-79 GPa) is much lower than that of chromium-molybdenum steel (200-207 GPa), and its tensile strength (over 246 MPa) is also lower than that of chromium-molybdenum steel (over 834 MPa), even with the same tube thickness, aluminum alloy often requires additional thickening to match the strength of chromium-molybdenum steel. Nevertheless, the total weight of an aluminum-framed bicycle is still less than half that of an iron-framed one, playing a key role in weight reduction [4]. 2. Corrosion Resistance: Compared with ordinary carbon steel, aluminum alloy exhibits better corrosion resistance. A thin natural oxide film easily forms on the surface of aluminum alloy, but it fails to prevent corrosive media from contacting the base metal. In contrast, pure aluminum reacts with oxygen in the air to form a dense aluminum oxide (Al_2O_3) film, which acts as an effective barrier against further contact between corrosive substances and the base metal, thereby achieving anti-corrosion effects [5]. 3. Environmental Friendliness: The lightweight nature of aluminum alloy reduces energy consumption and pollutant emissions during the product's lifecycle, aligning with environmental protection requirements. 4. Riding Efficiency Improvement: The use of aluminum alloy reduces material consumption, lowers riding resistance, and enhances riding speed. Additionally, studies have shown that for 2014-T6 aluminum alloy treated with anodization, as the oxide layer thickness increases, the initiation site of fatigue cracks shifts from the oxide layer surface to the alloy matrix surface, leading to a decrease in bending fatigue life. However, once the oxide layer reaches a certain thickness, the fatigue life stabilizes and no longer decreases with further increases in thickness [6].

2.1.2 Influence of Bicycle Materials on Riding and Mechanical Analysis and fluid Mechanics Perspective Analysis

Taking a standard bicycle as an example, a high-carbon steel frame typically weighs 18-20 kg, while an aluminum alloy frame reduces the weight to 12-14 kg. According to Newton's second law ($F = m \times a$), a reduction in mass (m) directly decreases the force (F) required for riding. During cycling, the frame bears the rider's weight, road reaction forces, and various dynamic loads. The aluminum alloy frame efficiently distributes these forces, ensuring that the forces are dissipated through the pedals and wheels, minimizing vehicle deformation and rider fatigue. Thus, choosing a lighter bicycle is an effective way to increase riding speed. From the perspective of riding scenarios, during uphill climbing, the gravitational force formula ($F = G \times sin\theta$, where G is total gravity and θ is the slope angle) applies. A lighter aluminum alloy bicycle reduces the total gravity (G), thereby decreasing the uphill force (F). Practical tests indicate that under the same conditions, aluminum alloy bicycles require approximately 10% less power to climb slopes compared to high-carbon steel bicycles.

In fluid mechanics, the air resistance formula is expressed as $F ? = 1/2 \rho \times v^2 \times C_a \times A$, where: F_a = Air resistance; ρ = Air density; v = Riding speed; C_a = Drag coefficient; A = Windward area. During riding, air resistance accounts for over 70% of total resistance, so reducing the drag coefficient (C_a) and windward area (A) is the core strategy for saving energy. First of all, streamlined Section Design: Aluminum alloy has excellent plasticity, allowing frame tubes (top tube, down tube, seat tube, etc.) to be designed with streamlined cross-sections instead of traditional circular ones. Data shows that under the same tube diameter, the drag coefficient of a streamlined section (0.28) is significantly lower than that of a circular section (0.45), minimizing the force riders need to overcome air resistance. Moreover, windward Area Reduction: On the premise of ensuring structural strength, reducing the tube diameter can decrease the windward area by 15%-20%. As indicated by the formula, a smaller windward area (A) directly reduces air resistance. For example: the Specialized S-Works Venge serves as a typical example of fluid mechanics application in bicycle design. Its carbon fiber frame is engineered for aerodynamics, with seat stays designed to mimic aircraft wings using FACT carbon fiber curved airfoils, effectively reducing air resistance [7]. And China's production capacity of high-performance carbon fiber accounts for only about 0.4% of the global total, and over 90% of domestic demand relies on imports, resulting in a near shortage [8]. However, despite carbon fiber's superior yield strength and portability, its high cost remains a significant limitation.

2.2 Modeling and Assembly

2.2.1 Overall Modeling Concept

In this study, SolidWorks 2024 was employed as the primary modeling tool to design the overall structure of the folding bicycle frame. As the core component of a folding bicycle, the frame's design quality directly impacts the vehicle's safety, convenience, and service life. Frame design must balance structural strength and folding portability, so the following key aspects were prioritized during modeling: Structural Rationality: This directly influences the frame's contribution to overall vehicle stability. The frame must possess sufficient strength to withstand the rider's weight and external impacts. Lightweight and Applicability: Material selection indirectly affects vehicle performance. Frame cross-sectional design was derived from fluid mechanics calculations, and material choices were optimized to reduce vehicle weight. Folding Reliability and Durability: The connection strength and long-term durability of the folding mechanism were ensured through structural design.

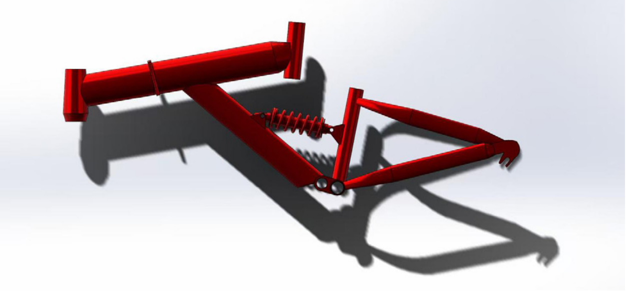

Fig. 1 3D Modeling of the Bicycle Frame in SolidWorks 2024

As shown in Figure 1, the 3D model was constructed in SolidWorks 2024 based on the actual design dimensions and parameters of the folding bicycle frame. The frame primarily uses rectangular and circular structures for modeling, which not only reduces wind resistance and meets lightweight requirements but also maintains high structural strength. Additionally, the design and installation of the folding structure were integrated into the modeling process to ensure stability during both folding and riding.

2.2.2 Component Design

The frame model consists of a main tube, top tube, down tube, seat tube, seat stays, chain stays, seat post, and central shock absorber. The main frame is composed of

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hollow circular tubes, while the front and rear forks adopt rectangular (streamlined) designs. A shock absorber is installed at the central connection to enhance riding comfort and vehicle stability. Key component specifications are as follows:

1. Main Tube: As the primary load-bearing structure, it is made of rectangular hollow aluminum alloy with a wall thickness of 2.5 mm to improve tensile performance and durability.
2. Seat stays and Chain stays: These are welded to the main tube and seat tube. Cutting and chamfering processes were applied during modeling to ensure geometric compatibility with the main tube. Seat stays: Cross-section of 25 mm×15 mm, wall thickness of 1.8 mm. Chain stays: Cross-section of 30 mm×18 mm, wall thickness of 2 mm
3. Folding Mechanism: A critical component determining folding smoothness and service life, its structure was optimized to ensure reliable connection and easy operation.
4. Seat Tube and Seat Post: The seat tube is a circular hollow aluminum alloy tube (diameter 28 mm, wall thickness 2.2 mm) vertically connecting the main tube and rear fork, ensuring welding strength with the seat stays and chain stays. The seat post features an embedded design (outer tube diameter 30 mm, inner tube diameter 27 mm) with a lockable height adjustment function, adapting to riders of different heights while maintaining folding coordination.
5. Top Tube and Down Tube: These connect the main tube and seat tube. The top tube is a hollow aluminum alloy tube (diameter 32 mm, wall thickness 1.8 mm), while the down tube uses a streamlined hollow cross-section (40 mm long axis, 20 mm short axis, 2 mm wall thickness) to reduce drag coefficient, with the hollow structure further reducing weight.

2.2.3 Optimized Frame Modeling

To balance weight reduction and structural integrity, the following optimization measures were implemented: Hollow Design for Low-Stress Areas: Non-critical stress-bearing parts were designed with hollow structures to reduce total weight without compromising strength. Aerodynamic Enhancement: Aerodynamic features were integrated to improve riding speed by minimizing air resistance. Strengthened High-Stress Areas: High-stress components were reinforced with robust structures and materials to prevent deformation or damage during high-speed riding. Folding Mechanism Optimization: Connection structures were refined to ensure smooth folding and reduce jamming. Emerging design concepts were also referenced, such as: Recumbent Bicycles: These reduce wind resistance and improve riding comfort by altering the rider’s posture. And mounted Bicycles: Featuring no transmission system, riders are mounted under the frame and propel the vehicle by foot sliding [9].

2.3 Mechanical Analysis

This study utilized the Simulation plugin in SolidWorks 2024 for mechanical analysis, investigating the finite element distribution and deformation behavior of the frame by establishing a finite element model. Relevant references provide support for this approach: taking a folding bicycle frame as the research object, a 1:1 3D model was built in SolidWorks. In the Simulation module, load conditions consistent with actual riding (a rider weight of 60 kg, with 70% of the gravity distributed to the seat and 30% to the pedals) were set for static simulation, resulting in a maximum frame stress value of 1.9×10^6 N/m². Meanwhile, a physical test platform was constructed, and strain gauges were used to measure the actual stress at key frame locations (the connection between the seat tube and main tube). The results showed that the error between the simulated and measured values was only 3.2%, verifying the reliability of SolidWorks Simulation in the static mechanical analysis of bicycle frames [10].

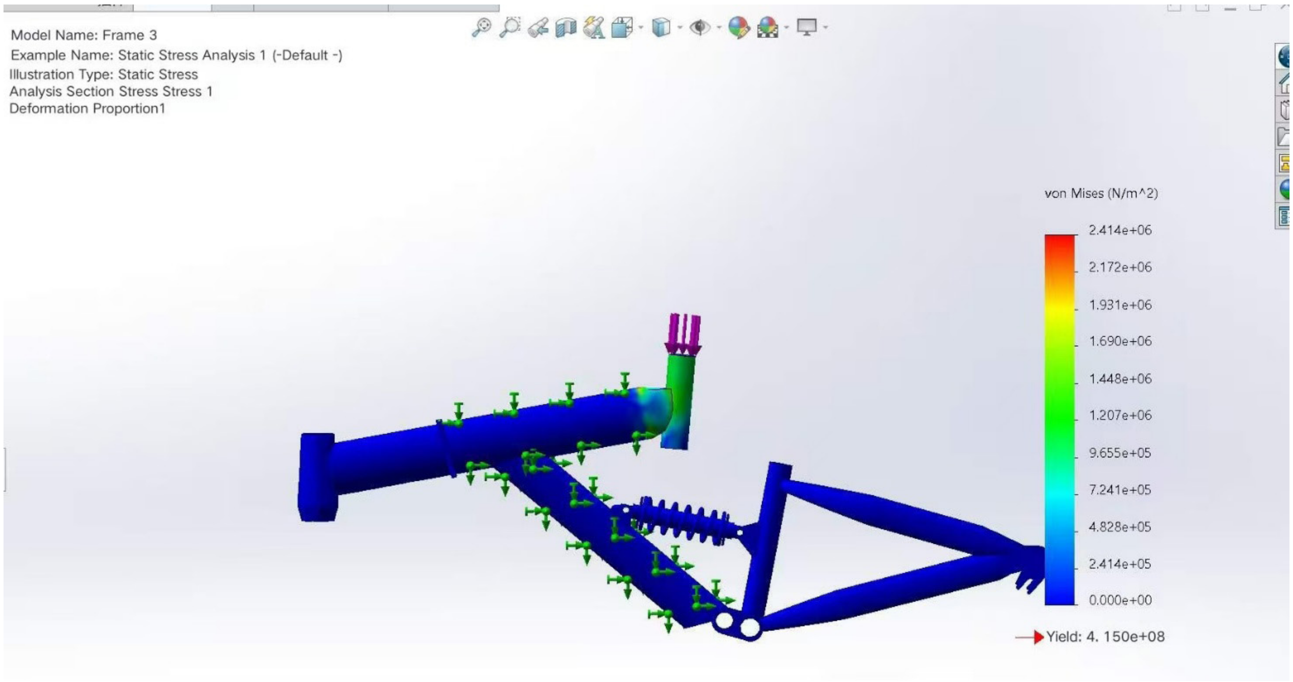

Fig. 2 Stress Analysis via the Simulation Module

The mechanical analysis image shown in Figure 2 was obtained by applying pressure to the seat tube and accounting for gravitational effects.

2.3.1 Static Analysis

A rider weight of 60 kg was assumed, with gravity distributed between the seat and pedals. For mechanical analysis during dynamic riding, deceleration forces or impact forces were simulated in specific scenarios and calculated proportionally with gravity. Torsion force analysis was also conducted to simulate the torsional stress exerted on the frame when the bicycle turns.

2.3.2 Analysis Results

The analysis results indicated that the stress value of the frame ranged from 0 to 2.414×10^6 N/m². Color coding provides an intuitive reference: blue represents low-stress areas, while red indicates high-stress areas.

The 2014-T6 aluminum alloy used in the frame has the following chemical composition (by mass fraction, %): Fe 0.30, Cu 4.30, Mg 0.51, Mn 0.66, Si 0.70, Zn 0.13, Ti 0.02, Cr 0.03 [6]. Its material properties are presented in Figure 3 and Table 1.

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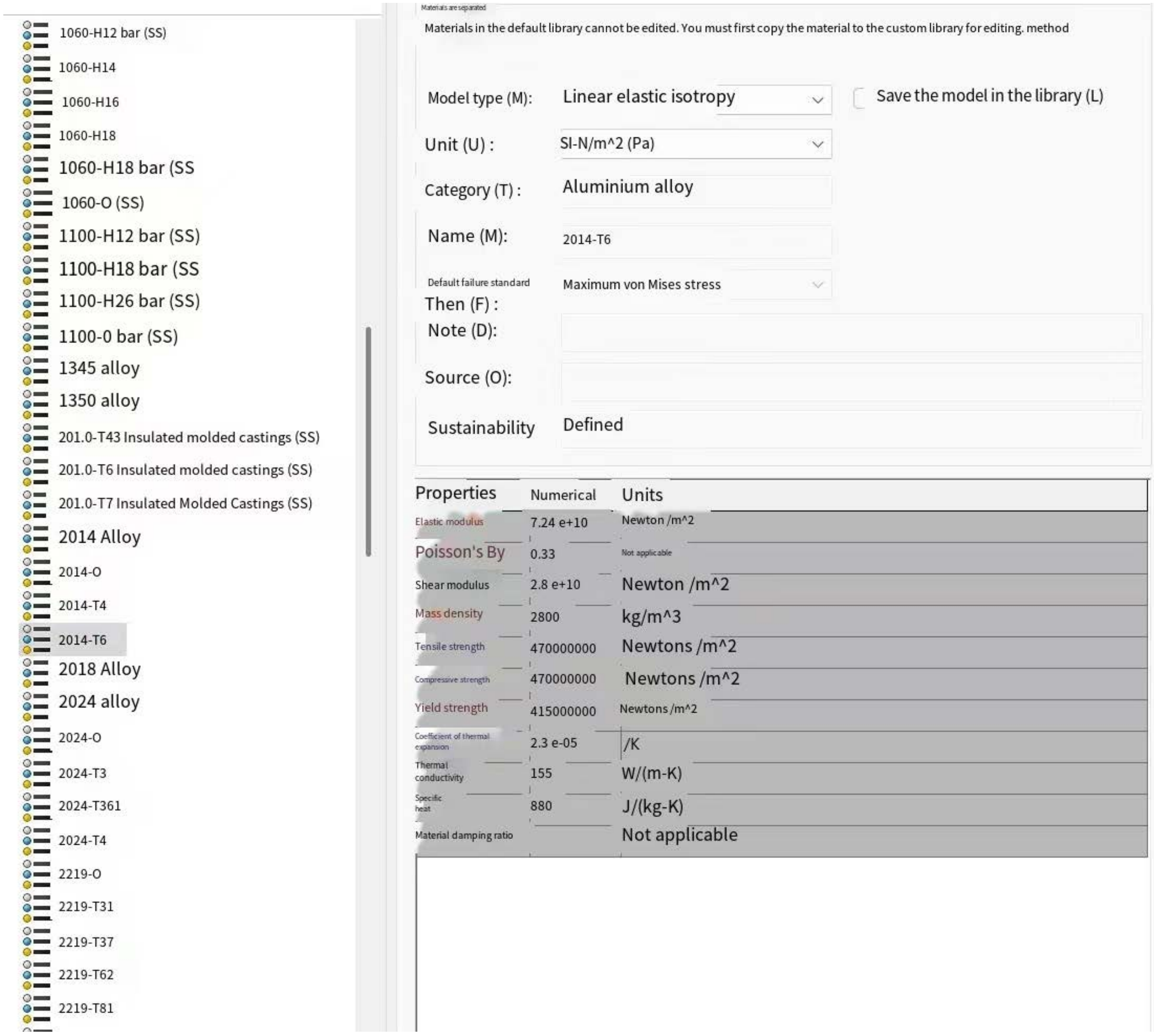

Fig.3 Properties of 2014-T6 Aluminum Alloy

Table 1. Details of Material

Detail1	Value 1	Detail 2	Value 2
Elastic Modulus (N/m²)	7.24e+10	Poisson's Ratio	0.33
Shear Modulus (N/m²)	2.8e+10	Mass Density (kg/m³)	2800
Tensile Strength (N/m²)	470000000	Compressive Strength (N/m²)	470000000
Yield Strength (N/m²)	415000000	Coefficient of Thermal Expansion (/K)	2.3e-0.5
Thermal Conductivity (W/(m-K))	155	Specific Heat (J/(kg-K))	8880

Local stress concentration was observed in areas such as the connection between the seat tube and main frame (green part), with stress values ranging from 1.207×10^6 to 1.931×10^6 N/m². However, this remains well below the dangerous threshold relative to the material's yield strength.

2.3.3 Optimization Directions Based on Results

Lightweight Design: Given that most areas of the frame appear blue (indicating low stress), hollow designs and material reduction techniques (e.g., local tube thinning and hollow structures) can be applied to non-critical stress areas. This approach reduces overall weight while preserving structural strength and extending the frame's service life.

Improvement of Stress Concentration Areas: For regions with local stress concentration, measures such as adding fillets, local material replacement, and structural reinforcement can be implemented to alleviate stress levels, reduce fatigue damage from long-term use, and prolong the frame's service life.

3. Conclusion

This study investigated folding bicycle frames through 3D modeling, assembly, and simulation analysis using SolidWorks 2024. By integrating principles from fluid mechanics, structural mechanics, and materials science, several key conclusions were drawn:

Effectiveness of Modeling and Material Selection: The adoption of streamlined cross-sections, reduced tube diameters, and the use of 2014-T6 aluminum alloy led to an approximate 35% reduction in frame weight. The maximum stress value of the frame was below 1.931×10^6 N/m^2, which is well below the yield strength of the material, fully meeting the requirements for daily riding. Guarantee of Folding Performance: Through the optimization of the folding mechanism's design and structure, the frame was verified to withstand the riding load of an adult, achieving a balance between safety and performance. Advancements from Fluid and Structural Mechanics Research: Reducing the tube diameter and adopting a more streamlined cross-section significantly improved riding efficiency and effort-saving performance, addressing major pain points in practical use. However, this study also has limitations: Insufficient Material Exploration: Due to cost considerations and technical maturity, in-depth comparative modeling and mechanical analysis of carbon fiber composites were not conducted, despite their potential advantages. Moreover, lack of Long-Term Performance Research: The study did not investigate wear of folding joints or the decline in precision after long-term use, nor did it perform corresponding simulation studies or experiments on long-term stability. And incomplete Mechanical Analysis: Only static mechanical analysis was carried out, while tests on jolty resistance and fatigue performance under dynamic riding conditions were not conducted, failing to fully replicate real-world riding scenarios. Also, there is some future research prospects are proposed as follows: Material Innovation: With the development of carbon fiber composites, their application in folding bicycle frames should be explored to further reduce weight while enhancing overall vehicle stability. Currently, carbon fiber has long been regarded as a strategic material, with most countries imposing export restrictions. In-Depth Dynamic Analysis: Advanced fatigue analysis techniques should be applied to conduct more in-depth dynamic analysis, and more sophisticated modeling software should be used to optimize modeling processes and algorithms. Folding Mechanism Improvement: The folding mechanism should be upgraded, and wear tests should be conducted to maximize service life and enhance safety and reliability.

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