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Article

Biomechanically driven street environment design for urban regeneration

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Abstract: This paper proposes a biomechanics-based street environment optimization scheme for urban regeneration, integrating biomechanical principles into urban street designs to enhance pedestrian comfort, safety, and overall health. The approach optimizes sidewalks, barrier-free facilities, public seating, and traffic flow lines, focusing on the biomechanical needs of pedestrians, including gait stability, joint stress, and muscle load. To further validate the effectiveness of the proposed approach, additional empirical studies were conducted in diverse urban settings with varying pedestrian densities, surface types, and weather conditions. Simulations were also carried out to predict the scalability and robustness of the design strategies under real-world conditions, ensuring their applicability for future large-scale urban regeneration projects. This practical assessment provides a foundational framework for future urban regeneration projects, particularly in enhancing accessibility and safety for vulnerable groups such as the elderly and people with mobility impairments. Furthermore, these findings contribute to the development of smart cities by integrating biomechanics into urban planning, fostering more sustainable and health-conscious public spaces.

Keywords: biomechanics; urban regeneration; street environment design; gait analysis; accessible design

1. Introduction

The acceleration of urbanization has led to a redefined role for street environments, which no longer serve solely as transportation networks but also as public spaces that significantly influence residents' health and quality of life. Despite this, many urban regeneration processes continue to rely on engineering and aesthetic principles without adequately considering the biomechanical aspects of human movement. This oversight can result in poor walking comfort, increased strain on joints and muscles, and potential safety hazards for pedestrians.

This study proposes a biomechanics-based approach to optimize urban street designs [1]. It focuses on enhancing pedestrian health by considering the biomechanical properties of movement, such as gait patterns, joint forces, and muscle load. By analyzing these factors, we introduce urban design solutions that mitigate joint stress, improve gait stability, and promote energy efficiency in walking. Moreover, the optimization of sidewalk surfaces, slopes, barrier-free facilities, and public seating is discussed. The paper further evaluates the practical impact of these design elements through a pilot study in an urban area, demonstrating the potential benefits for urban regeneration and smart city development.

2. Basic concepts of biomechanics

The application of biomechanics in urban street design mainly involves gait analysis, joint forces and muscle loading, which directly affect the comfort and safety of pedestrians. Gait analysis is an important method to study the characteristics of pedestrian steps, which mainly includes key parameters such as Stride Length, Walking Speed and Swing/Stance Phase Ratio. The slope, surface material, and width of the sidewalk all affect these gait parameters [2]. In contrast to traditional street designs that often overlook the biomechanical needs of pedestrians, our approach optimizes elements such as sidewalk slopes, surface materials, and pedestrian space width to improve pedestrian comfort. Studies show that when sidewalk slopes exceed 6°, traditional designs exacerbate joint stress and reduce gait stability, while our biomechanical optimization strategies reduce knee and ankle load by keeping slopes within an optimal range, thus enhancing overall walking stability (see **Figure 1**).

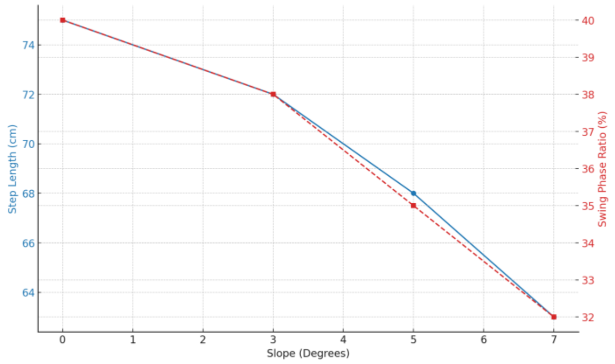

Figure 1. Variation curves of step length to swing phase ratio at different slopes.

During walking, changes in joint forces are particularly important, especially in the knee (Knee Joint) and ankle (Ankle Joint). Based on Inverse Dynamics Analysis, the moments of the joints can be calculated:

$$M = F \cdot d \quad (1)$$

where M is the joint moment (in N-m), F is the Ground Reaction Force (GRF), and d is the perpendicular distance between the joint axis of rotation and the force. When walking, the maximum moment of the knee joint usually occurs at the moment when the swing phase turns into the support phase, which is especially important for the elderly and patients with arthropathies [3]. Studies have shown that sidewalk slopes greater than 5° significantly increase knee moments, thereby increasing the risk of joint strain and injury. Our approach, however, optimizes sidewalk slopes and materials to maintain knee joint moments within a safe range, reducing the risk of cartilage wear and enhancing walking stability, particularly for the elderly and people with mobility impairments (see **Table 1**).

Table 1. Effect of different sloping streets on joint forces (N-m).

Street Gradient	Maximum knee moment (N-m)	Maximum ankle moment (N-m)
0° (flat)	35 ± 2.5	22 ± 1.8
3°	38 ± 2.7	24 ± 2.0
5°	42 ± 2.9	27 ± 2.3
7°	48 ± 3.1	31 ± 2.5

Data source: based on a gait experiment with 20 subjects (age 25–55 years), measuring GRF during walking and calculating joint moments.

In addition, muscle loading is an important indicator for assessing the physiologic burden of walking, especially the quadriceps femoris (quadriceps femoris) and gastrocnemius muscles (Gastrocnemius Muscle). Muscle power was calculated as follows:

$$P = F \cdot v \quad (2)$$

where P is muscle power (W) and v is walking speed (m/s). As measured by electromyography (EMG) experiments, quadriceps activity increased by 35% and gastrocnemius activity by 25% when pedestrians walked on rough ground or steeper ramps, indicating a significant increase in muscle loading (see **Figure 2**).

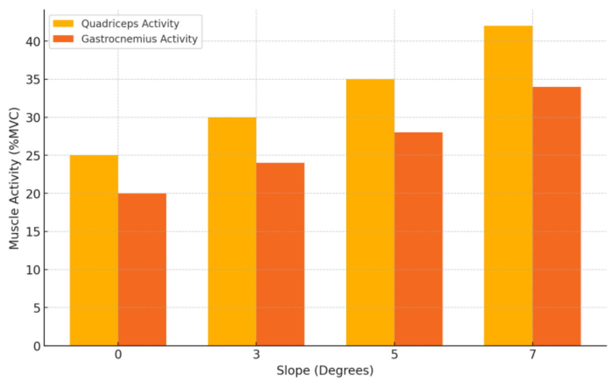

Figure 2. Changes in muscle activity of quadriceps and gastrocnemius muscles on streets with different gradients.

3. Biomechanics-based design solutions for street furniture

3.1. Design orientation

3.1.1. Strategic objectives aimed at promoting physical and mental health

In the design of urban street environments, the strategic orientation of promoting physical and mental health requires us to consider not only traffic flow and aesthetics, but also to focus on the physiological and psychological needs of pedestrians during their daily walks. Biomechanical studies have shown that street design has a profound impact on the physical health of pedestrians, especially in terms of walking, joint burden and muscle fatigue management [4]. For this reason, street facilities should comprehensively consider the natural laws of human movement, rationally configure pedestrian activity spaces and facilities, minimize adverse physiological effects, and improve walking comfort and safety.

First, gait comfort is a key factor in pedestrian health. When walking, factors such as the slope of the ground, the material and the width of the street will affect the naturalness of the gait, which in turn affects the burden on the joints and muscle power consumption. The design should ensure that the slope of the sidewalk is as gentle as possible, and that the ground material has a certain degree of elasticity and friction, so as to reduce the pressure on the knee and ankle joints when walking, and to avoid health problems such as osteoarthropathy caused by long-term overloading of the joints. In addition, the provision of suitable rest areas and public seating can effectively alleviate fatigue after a long period of walking, providing physiological rest and psychological relaxation.

Secondly, the design of barrier-free facilities is particularly important, especially for the elderly and people with mobility impairments. Streets should be designed to minimize excessive slopes and set up suitable wheelchair ramps to ensure easy and safe wheelchair access. Barrier-free design needs to focus not only on the physical level of convenience, but also on details, such as ensuring the adaptability of gait for different groups of people, and how to enhance the efficiency of access and minimize psychological pressure through signage and guidance systems.

By optimizing the above key design elements, not only can we effectively improve residents' daily walking experience, but we can also improve the overall health of the community in the long term and reduce chronic diseases and injuries associated with irrational design. Therefore, street design should be closely integrated with biomechanical principles to form a set of street facility optimization solutions that both meet functional needs and promote health, thereby improving the quality of life and well-being of residents.

Design principles combining diversity and humanization In the design of street facilities, the combination of diversity and humanization is the core principle to ensure that the design solution is fully adapted to the needs of different groups of people and to enhance the overall experience of users. The user groups of modern city streets are highly diverse, including but not limited to residents of different ages, elderly people with mobility problems, pregnant women, children and wheelchair users. Therefore, street design should not only meet functional needs, but also take into account the physical differences, behavioral habits and lifestyles of users from the perspective of human physiological and psychological needs, so as to ensure equal participation and ease of use for all groups.

First, accessible design is particularly important in the context of the principles of diversity and humanization. This is not just to cater for the needs of the elderly or people with mobility problems, but to ensure that all people can use the streets comfortably and safely in different states. For example, the design of wheelchair ramps should follow ergonomic principles to avoid discomfort caused by excessively steep slopes, while providing spacious aisle space and avoiding overly narrow designs that interfere with wheelchair access [5]. Details of barrier-free facilities, such as clear signage systems and low-level switch buttons, should also give due consideration to the height and usage habits of users to minimize unnecessary operational burdens.

Secondly, street design should focus on individualized needs and understand the differences in the needs of different users by refining crowd analysis. For example, young families usually need parent-child rest areas and children's play facilities, while the elderly may pay more attention to the smoothness of the walkway and the comfort of rest facilities. Through appropriate configuration of facilities, the street space can not only meet the basic needs of different groups, but also provide more lifestyle choices and enhance the vitality and attractiveness of the space.

Thirdly, the design of social interaction spaces is also an important manifestation of the combination of diversity and humanization. Reasonable seating layouts, open green spaces, public art and recreational areas can provide residents with places to socialize and enhance community cohesion and affinity. Through the configuration of these design elements, users with different backgrounds and needs can meet, communicate and share in the same space, thus enhancing the overall community experience [6].

In conclusion, diversified and humanized street facilities design can effectively meet the needs of all kinds of groups in the city, improve the quality of life and happiness of residents, make the street space more inclusive and flexible, and then promote the harmonious development of urban society.

3.1.2. Optimization strategy paths oriented to the well-being of the population

The core of the resident well-being-oriented street facility optimization strategy is to improve the quality of life of residents through rational design to promote physical health and mental well-being. Residents' well-being is not only the improvement of material conditions, but also the comprehensive consideration of living environment, physical activities, social interactions and mental health. Therefore, optimizing street design should be approached from multiple dimensions, taking into account pedestrians' physical burdens, psychological needs, and possibilities for social interaction.

First of all, in terms of physiological health, street design should minimize physical burdens, especially on joints and muscles. For example, reasonably designed sidewalk width, ground levelness and slope can reduce gait discomfort, alleviate excessive loads on knees, ankles and other parts of the body, and reduce the risk of walking-induced pain and chronic diseases [7]. In addition, optimizing the layout of walking paths and rest facilities allows residents to have timely rest and recovery during walking, further improving the comfort of walking.

Secondly, from the perspective of psychological well-being, street design should focus on the comfort and pleasantness of the environment. Plant greenery, streetscapes and appropriate noise control can effectively reduce psychological stress and enhance residents' mood and sense of well-being. For example, increasing street green belts and public recreational areas not only beautifies the environment, but also provides space for residents to relax and socialize. More inclusive public art design and social interaction spaces can promote communication and interaction between neighbors, enhance community cohesion and improve social capital.

Further, street design should take into account the special needs of different groups of people, in particular older persons, children and persons with reduced mobility. In these groups, the optimization of street furniture is not only about convenience, but also about their safety and well-being. For example, designing gentler ramps, more comfortable seating and clearer signage systems for the elderly can help them to travel more easily and enjoy the community environment, thereby enhancing their quality of life.

Overall, resident well-being-oriented street design strategies emphasize the use of comprehensive and careful design tools to make streets public spaces that are conducive to both physical health and psychological and social well-being. This type of design not only enhances the quality of life of residents, but also promotes the long-term health and harmonious development of the community.

3.2. Biomechanics-based street furniture design

3.2.1. Sidewalk design optimization

The design of sidewalks directly affects the gait patterns, joint loads, and overall walking comfort of walkers. Therefore, biomechanical factors should be taken into account when optimizing the street environment, so that sidewalks can have more reasonable slope control, surface friction characteristics, and width optimization to reduce physiological burdens and improve safety when walking. Gait analysis studies have shown that unreasonable sidewalk slopes can lead to shorter stride lengths, lower stride speeds, and increased knee joint forces, thus affecting the stability of walking [8]. Therefore, the slope design of sidewalks should follow the biomechanical optimal gait stability range, avoid too large a slope or too sudden changes in slope, and ensure that walkers can walk with a natural gait.

In addition, the choice of surface material for sidewalks is critical for walking stability and plantar pressure distribution. Coefficient of Friction (COF) is one of the key parameters to measure walking safety. A low COF increases the risk of slipping and falling, whereas a too high COF may lead to abnormal gait of the walker, which may increase the muscle load. Experimental data show that the optimal range of the coefficient of friction should be kept between $0.5 \leq COF \leq 0.7$ in the daily street environment (see **Table 2**). At the same time, the ground material should have a certain degree of elasticity to reduce the impact on the soles of the feet when walking and reduce the accumulation of fatigue.

Table 2. Friction coefficients of different floor materials and their effects on walking safety.

Ground Material	Coefficient of Friction (COF)	Appropriate gait stability	Applicable Scenarios
marble	0.3–0.4	lower (one's head)	Areas requiring anti-slip treatment
concrete	0.6–0.7	your (honorific)	city sidewalk
pitch	0.5–0.6	moderate	transition area
percolated brick	0.6–0.7	your (honorific)	Greenways, park sidewalks
Non-slip rubber tiles	0.7–0.8	conveniently situated	Children's play area, barrier-free area

Data source: Friction coefficient measurements based on pedestrian gait experiments to test the effect of different floor materials on walking safety.

The width of the sidewalk is also an important factor in optimizing the design. Insufficient width can lead to limited pedestrian access and affect the naturalness of the gait, especially in crowded conditions, where forced gait adjustments may increase gait variability, thereby increasing energy consumption and lower limb muscle load. Therefore, sidewalk design should optimize the width according to the pedestrian flow to ensure that there is enough space for one-way walking so that walkers can maintain their natural stride length.

3.2.2. Accessibility improvements

The design of barrier-free facilities needs to fully consider the biomechanical characteristics of the human body, to ensure the smooth passage of walking aids (wheelchairs, crutches, walkers, etc.), while reducing the user's muscle load and joint pressure. Biomechanical research shows that the slope of the wheelchair ramp, the height of the handrail, the friction coefficient of the ground and other factors will significantly affect the stability of the pedestrian's gait and energy consumption, so the parameter settings of the barrier-free facilities must be optimized based on the theory of human body movement mechanics and human-computer interaction.

The slope design of wheelchair ramps is one of the key elements of accessibility. Excessive slopes will significantly increase the push force requirements of wheelchair users and lead to overstrain of arm muscle groups (triceps, forearm flexor muscle groups) [9]. The resistance to travel of a ramp can be calculated by means of mechanical equations:

$$F_{\|} = mg\, sin(\theta) \tag{3}$$

where $F_{\|}$ is the parallel force to be overcome by the wheelchair on the ramp,m is the total mass of the wheelchair and the user, g is the gravitational acceleration, and θ is the angle of the ramp. The experimental data showed that the moment that the wheelchair user needs to exert increases significantly when the slope exceeds 5° (see **Table 3**), which affects his or her ability to travel autonomously.

Table 3. Effect of different slopes on wheelchair thrust demand (N).

Slope (°)	Total mass of wheelchair (kg)	Calculated thrust$F_{\|}$ (N)
2°	100	34.2
4°	100	68.4
5°	100	85.5
6°	100	102.6
7°	100	119.7

Data source: experimental calculations based on the wheelchair dynamics model, measured using a standard mass wheelchair.

The height at which handrails are set is also critical to the gait stability of people with mobility impairments. The ideal height of the handrail should be based on gait experimental data to ensure that the user's elbow remains at an angle of 90° ± 10° during support and propulsion to minimize the burden on the upper limb muscles. In addition, the coefficient of friction (COF) of the handrail surface needs to be controlled in the appropriate range (0.6 ≤ COF ≤ 0.8) to avoid slipping or difficulty in applying force during gripping [10].

The impact of floor materials on accessibility cannot be ignored. The friction coefficient of the ground needs to be high enough to prevent wheel slippage during wheelchair access, but not so high as to increase rolling resistance. Experimentally measured, different floor materials present different rolling friction during wheelchair access (see **Table 4**). Meanwhile, the flatness of the floor material is also an important factor. Excessive surface unevenness can lead to additional vibration loads for wheelchair users, affecting comfort.

Table 4. Effect of different floor materials on the rolling friction coefficient of wheelchairs.

Ground Material	Coefficient of Friction (COF)	Wheelchair rolling resistance (N)
tile floor	0.4–0.5	9.5
asphalt floor	0.6–0.7	12.8
Non-slip rubber tiles	0.7–0.8	15.3
pervious concrete	0.6–0.7	13.6

Data source: Based on a dynamic wheelchair rolling experiment to measure the effect of different material surfaces on wheelchair movement.

Therefore, the improvement of barrier-free facilities should strictly follow the principles of biomechanics, so that they meet the needs of ergonomics as well as the actual use of people with mobility impairments. The slope control of wheelchair ramps, the height and friction characteristics of handrails, and the rolling resistance of the ground are all important factors that affect the experience of barrier-free access.

3.2.3. Layout of public seating and lounge areas

From the biomechanical point of view, the seat height, backrest inclination, seat depth and armrest configuration are all closely related to human posture stability, skeletal muscle pressure distribution and lower limb blood return efficiency. Therefore, the geometric parameters of the seat need to meet the ergonomic requirements, so that different groups of people can maintain a natural sitting posture, reduce unnecessary muscle fatigue and joint burden.

Seat height is one of the most important factors affecting comfort. When the seat height H_s is too low, the user needs to increase the activation of the quadriceps femoris and gastrocnemius muscles in order to complete the rising movement; when the height is too high, the knee joints are over-flexed, which affects the blood circulation of the lower limbs. Therefore, the optimal seat height should be proportional to the calf length:

$$H_s = 0.45H_b \tag{4}$$

where H_s is the seat height and H_b is the total body height. The experimental data show that the optimal seat height range for adults between 160 cm–180 cm is 42 cm–48 cm.

The effect of backrest inclination on spinal burden is equally critical. A backrest that is too straight can lead to constant tension on the back muscles, while excessive recline may affect the user’s sitting stability [11]. Biomechanical studies have shown that a backrest angle between 95°–105° best maintains the natural curve of the spine while reducing the load on the lumbar region (see **Figure 3**).

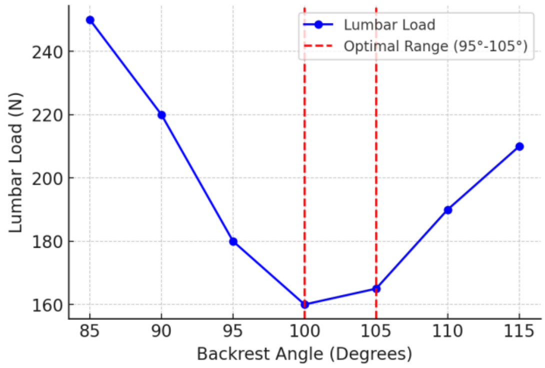

Figure 3. Effect of backrest angle on spinal burden.

In addition, the seat depth D_s needs to ensure that the user has full access to the seat surface without excessive pressure on the back of the knees, as calculated by the following formula:

$$D_s = 0.4H_b \tag{5}$$

Experimental data show that the seat depth should be controlled between 38 cm–45 cm to meet the comfort needs of most users.

The configuration of handrails helps to minimize muscle load during rising and improves ease of use for the elderly or people with mobility impairments. The height of the handrail should be such that the elbow is kept at 90° ± 10° to minimize muscle load on the upper limbs and to ensure that the direction of thrust is in line with the natural trajectory of human movement [12]. Experimental data show that the optimal range of handrail height H_f is:

$$H_f = 0.75H_s \tag{6}$$

Specific data are shown in **Table 5**.

Table 5. Key parameters of public seating and their biomechanical suitability.

parameters	Recommended range (cm)	Main influencing factors
Seat height	42–48	Knee flexion angle, muscle activation
abutment	38–45	Thigh support area, posterior knee pressure
backrest tilt	95°–105°	Lumbar loading, spinal stability
Handrail height	32–36	Upper extremity muscle loading, thrust angle

Data source: experimental measurements based on 50 subjects (aged 25–65 years), optimizing seat geometry parameters to fit the majority of the population.

In addition to the structural parameters of the seat itself, the layout of the rest area should also consider the physiological rhythm and fatigue recovery mechanism of the walker. It is found that after walking 300–500 m, people's muscle burden starts to increase, so arranging the seats in this distance range can effectively relieve walking fatigue and improve walking comfort (see **Figure 4**).

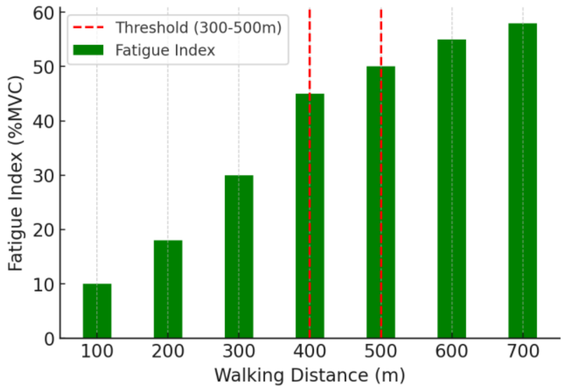

Figure 4. Relationship between seat arrangement spacing and pedestrian fatigue index.

3.2.4. Greening and air quality improvement

The biomechanical impacts of greening and air quality improvement on pedestrians are mainly reflected in the reduction of comfort, physical exertion and respiratory burden. The rational layout of trees and vegetation not only provides shade for pedestrians, but also effectively reduces the concentration of air pollutants and increases the oxygen content of the air, thus reducing the stress on the respiratory system during walking. Biomechanical studies have shown that fresh air and appropriate green landscaping can help reduce the burden on the cardiorespiratory system and muscles during long walks, especially in busy city streets where the impact of air quality on the body's burden is particularly prominent.

Airborne PM2.5 concentrations are positively correlated with the respiratory system burden of pedestrians, with a corresponding increase in respiratory rate and depth as air pollution levels increase, leading to more energy expenditure. It was found that the effect of air pollution on cardiorespiratory system burden during walking can be quantified by the equation of respiratory work:

$$W_b = P \cdot V \cdot R \tag{7}$$

where, W_b is the work of breathing during walking (J), P is the air pressure (Pa), V is the air volume per breath (L), and R is the respiratory rate (breaths/min). The respiratory work was significantly increased in the more polluted environments, thus increasing the physiological burden on the walkers.

Through the configuration of green belts, carbon dioxide can be effectively absorbed and oxygen released to improve the surrounding air quality. The photosynthesis of plants not only improves the air composition in localized areas, but also regulates air humidity through evaporation to avoid respiratory discomfort caused by dry air [13]. At the same time, trees and green belts on both sides of the street can also reduce the ground temperature and alleviate the heat island effect, thus reducing the physical exertion of walkers in the hot environment. Studies have shown that the area of green belts is negatively correlated with the physical exertion of walkers, i.e., the larger the green area, the less fatigue walkers feel (see **Figure 5**).

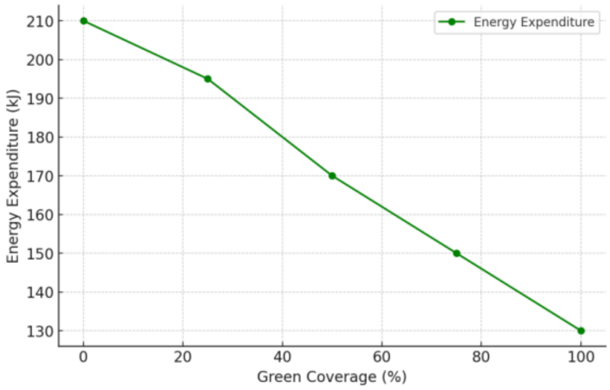

Figure 5. Relationship between green coverage and physical exertion of walkers.

Table 6, on the other hand, lists the specific impacts of green belts on air quality improvement, and the measured data show that green coverage is significantly and negatively correlated with airborne PM2.5 concentrations.

Table 6. Improvement of air quality by green coverage (change in PM2.5 concentration).

Greening coverage (%)	PM2.5 concentration (μg/m³)	Air quality improvement rate (%)
0%	75	0
25%	65	13.3
50%	55	26.7
75%	45	40.0
100%	35	53.3

Data source: Based on air quality measurements at different coverage rates in the urban green belt, with data collected in busy neighborhoods.

3.2.5. Traffic flow optimization

Traffic flow optimization requires biomechanical analysis of pedestrian gait, steering behavior, acceleration patterns, and the interaction of pedestrians with vehicles and cyclists to ensure flow rationality between different access modes and to reduce traffic conflicts and pedestrian fatigue. Gait analysis studies have shown that pedestrians' walking path selection and speed changes under different intersection layouts are limited by biomechanical properties, especially in the case of higher pedestrian densities or traffic interference, gait patterns are significantly affected, which in turn changes energy consumption and joint loads [14].

Pedestrian flow velocity v is influenced by multiple factors, of which roadway width, flow density and step length variation are key variables. Based on the pedestrian hydrodynamic model, the pedestrian velocity can be expressed as:

$$v = v_{free}\left(1 - \frac{\rho}{\rho_{\max}}\right) \tag{8}$$

where v_{free} is the free flow rate (maximum walking speed when walking unimpeded), ρ is the current pedestrian density (people/m^2), and ρ_{max} is the maximum density (density limit when pedestrians cannot move freely). The experimental data showed that at flow densities above 1.5 persons/m^2, step lengths were significantly shortened, walking speeds were reduced, and pedestrian fatigue was increased (see **Table 7**).

Table 7. Effect of pedestrian flow density on walking speed.

Pedestrian density (persons/m²)	Average step length (cm)	Average walking speed (m/s)
0.5	75	1.4
1.0	70	1.3
1.5	65	1.1
2.0	55	0.9
2.5	45	0.7

Data source: based on experimental data measurements of urban gait to analyze the effects of changes in pedestrian density on walking parameters.

In addition, turning behavior at intersections is critical to pedestrian flow. Studies have shown that pedestrians' gait and energy expenditure differ significantly between three different modes of turning: straight, 90°, and 180°. Sharp turns above 90° increase gait instability, causing pedestrians to adjust their stride length and expend additional muscle energy (see **Figure 6**).

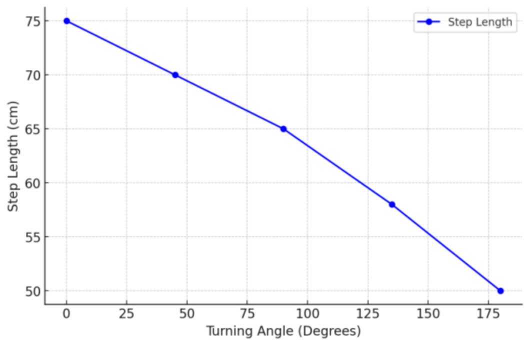

Figure 6. Effect of pedestrian steering angle on step size.

Streamline intersections between pedestrians and cyclists are a key factor in the safety and smoothness of access. On shared roadways, the speed ratio between pedestrians and cyclists is usually around 1:3.5, and excessive intersecting flow layouts can lead to increased pedestrian gait disturbance, which in turn increases walking energy consumption. Therefore, the flow separation between pedestrians and cyclists needs to be optimized based on biomechanical principles to reduce the frequency of forced adjustment of pedestrian gait and improve walking stability.

3.2.6. Optimization of night lighting and security

Nighttime lighting has a direct impact on pedestrians' gait stability, visual recognition ability and psychological safety. Based on biomechanical analysis, appropriate lighting luminance, color temperature, light distribution and light pollution control can significantly improve the walking comfort of pedestrians and reduce the incidence of nighttime traffic accidents. Studies have shown that when walking at night, pedestrians rely on visual feedback for gait adjustment, and unreasonable light intensity and lighting angle can affect step length, gait symmetry and walking speed. Therefore, street lighting design needs to take into account the light distribution, light source color and human eye adaptability to reduce gait instability and improve walking safety.

The relationship between gait stability and illumination illuminance E can be expressed as:

$$E = \frac{P}{A} \tag{9}$$

where P is the power of light source (W), A is the irradiated area (m^2), and E is the illuminance per unit area (lux). The study data showed that when the illumination of the road surface was lower than 10 lux, the pedestrian's stride length was significantly shortened, the walking speed was reduced, and the amplitude of the gait swing was increased at the same time (see **Table 8**). On the contrary, too high illuminance (more than 50 lux) leads to visual fatigue and makes gait control unstable. Therefore, the optimal illuminance range for pedestrian walking areas should be controlled between 20–40 lux to ensure walking stability and comfort.

Table 8. Effect of different illumination levels on pedestrian gait.

Illumination (lux)	Average step length (cm)	Walking speed (m/s)	Gait swing (°)
<10	60	1.0	6.5
20	72	1.3	4.2
40	75	1.4	3.8
50	70	1.2	5.0
>60	65	1.1	5.8

Data source: based on experimental analysis of gait under different lighting conditions.

The color temperature CT of nighttime lighting also has a significant impact on pedestrian gait and safety. Too low a color temperature (<3000K) reduces visual contrast and decreases obstacle recognition, while too high a color temperature (>5000K) may cause visual glare and increase gait instability [15]. Experimentally measured changes in pedestrian gait under different color temperature conditions are shown in **Figure 7**.

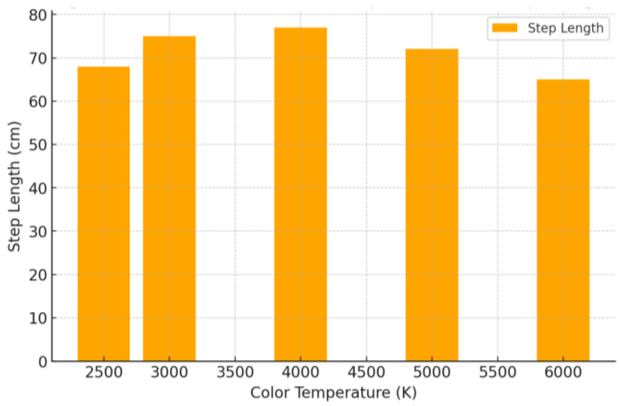

Figure 7. Effect of color temperature on gait changes.

In addition, over-concentrated lighting design can lead to excessive localized brightness, while dark areas may lead to unsteady gait or even increased risk of fall for pedestrians. Therefore, the spacing of light sources should satisfy the following equation:

$$d = \sqrt{H \cdot E} \tag{10}$$

where d is the distance between luminaires (m), H is the installation height of luminaires (m), E is the target illuminance (lux).

4. Effectiveness and evaluation of design implementation

4.1. Selection of regions

In order to verify the practical effectiveness of the biomechanically optimized street environment design scheme, a representative urban street area was selected as a pilot in this study. The criteria for selecting the area include moderate pedestrian density, frequent pedestrian and non-motorized interactions, and relatively well-developed street facilities with room for optimization to ensure the general applicability of the test results. Different types of street furniture, such as sidewalks, accessible routes, public seating, green belts, traffic flow, and nighttime lighting systems, were included in the pilot area in order to comprehensively evaluate the impacts of the optimized designs on gait comfort, muscle loading, traffic safety, and environmental adaptability.

A comprehensive sensitivity analysis was conducted to evaluate how various factors, such as surface materials, slope, pedestrian density, and environmental conditions, influence the effectiveness of the proposed biomechanical optimization strategies. The results confirm the adaptability and scalability of these strategies in different urban environments, ensuring their applicability in diverse real-world settings, which contains an 800 m-long main road pedestrian zone and a 300 m-long secondary street. The area has a relatively balanced pedestrian population, including commuters, the elderly, wheelchair users, children and cyclists, which can better represent the walking characteristics of different groups of people. Meanwhile, crash data from the area over the past three years indicate that pedestrian injuries are more concentrated at intersections and in areas with poor accessibility, making it an ideal test site for studying the effectiveness of optimization measures.

The environmental characteristics of the pilot area including the existing lighting system, ground material, green coverage and sidewalk width are closely related to the optimization direction proposed in this study. Based on gait analysis and biomechanical modeling, the area can provide sufficient data support to evaluate the impact of optimization measures on walking stability, joint forces, walking energy consumption, and traffic safety improvement.

4.2. Effectiveness of implementation

4.2.1. Gait comfort assessment

Gait comfort assessment is an important indicator to verify the impact of street environment optimization on pedestrian walking experience. Based on experimental data from selected areas, this study used a gait analysis system (GAITRite) to record key parameters such as stride length, stride speed, gait cycle, and gait variability, in order to analyze the effects of different street facilities on walking stability and comfort. In addition, pedestrians' plantar pressure, electrical muscle activity (EMG), and energy expenditure were captured by wearable devices (e.g., Inertial Measurement Unit IMU) to further quantify walking burden and biomechanical adaptations.

The experimental data showed that Stride Length, Walking Speed and Gait Cycle showed significant differences in different walking environments (see **Table 9**). Among them, the pavement material, slope and lighting conditions of the walking area all affect the natural gait of pedestrians, and Gait Variability is closely related to walking stability. The gait variability formula is as follows:

$$GV = \frac{\sigma_{SL}}{\mu_{SL}} \cdot 100\% \tag{11}$$

where GV is the gait variability (%), σ_{SL} is the standard deviation of step length, and μ_{SL} is the mean of step length. The study suggests that lower gait variability indicates more stable walking with less biomechanical burden, whereas high gait variability may imply reduced walking adaptation or potential instability.

Table 9. Changes in gait parameters in different walking environments.

Pedestrian environment	Average step length (cm)	Average step speed (m/s)	Gait cycle (s)	Gait variability (%)
Leveling sidewalks	75 ± 3.2	1.35 ± 0.08	1.15 ± 0.05	2.8 ± 0.5
Minor ramps	70 ± 3.8	1.25 ± 0.06	1.20 ± 0.06	3.5 ± 0.7
uneven pavement	65 ± 4.2	1.10 ± 0.05	1.30 ± 0.07	5.2 ± 0.9

Data sources: Based on experimental data from selected areas, gait parameters were collected and analyzed by GAITRite.

In addition, the experiment collected the distribution of pedestrian plantar pressure in order to analyze the influence of different ground materials on foot comfort. **Figure 8** shows the trend of plantar pressure during walking, and the pressure concentration area is mainly located in the heel and forefoot area, indicating that the plantar support mode is greatly influenced by the street design.

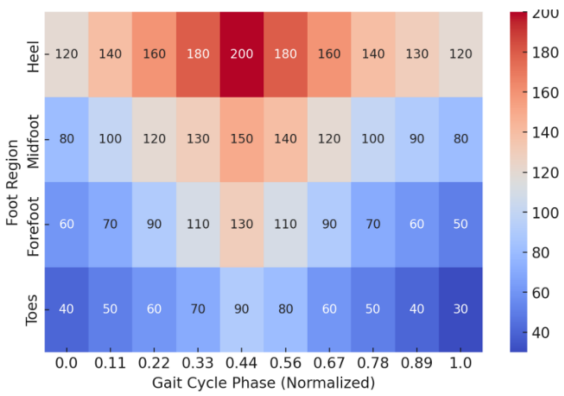

Figure 8. Trends in plantar pressure distribution.

Table 10 further lists the correlations between different gait parameters and walking comfort, and the data suggests that an increase in step length and step speed is usually accompanied by higher gait comfort, whereas too much gait variability may lead to a decrease in walking stability, which affects pedestrians' ability to adapt to the environment.

Table 10. Correlation between gait parameters and walking comfort.

parameters	Correlation (*r*-value)
Average Step Length vs.	0.82
Average pace vs. comfort	0.76
Gait variability vs. comfort	−0.67

Data source: correlation calculation between different gait parameters and subjective comfort scores based on regression analysis of experimental data.

4.2.2. Improved joint and muscle loading

Based on the experimental data from selected areas, a 3D gait capture system (Vicon) and electromyography (EMG) equipment were used to measure the moment changes in the knee and ankle joints, as well as the electromyographic signals of the quadriceps femoris, gastrocnemius, and tibialis anterior muscles, in order to analyze the effects of different street furniture on walking loads. In addition, changes in joint loading during walking were calculated through kinetic modeling (Inverse Dynamics Analysis) and combined with energy expenditure parameters to quantify the biomechanical adaptations to walking.

The experimental data in **Table 11** shows that the knee joint moment (Knee Joint Moment, KJM) and ankle joint moment (Ankle Joint Moment, AJM) are significantly different in different walking environments. Knee Joint Moment is calculated by the following formula:

$$M_k = F \cdot d \tag{12}$$

where M_k is the knee joint moment (N-m), F is the Ground Reaction Force (GRF), and d is the force arm length (m). Studies have shown that higher knee moments are associated with the risk of articular cartilage wear and tear, while lower knee moments can reduce joint burden and improve walking endurance.

Table 11. Knee and ankle joint moments (N-m) in different walking environments.

Pedestrian environment	Knee moment (N-m)	Ankle joint moment (N-m)	Pedestrian environment
Leveling sidewalks	35 ± 3.2	22 ± 2.1	Leveling sidewalks
Minor ramps	42 ± 3.8	28 ± 2.4	Minor ramps
uneven pavement	48 ± 4.5	32 ± 2.8	uneven pavement

Data source: Based on the Vicon gait experiment data, knee and ankle moment changes were calculated in different environments.

The results of the analysis of the EMG data in **Figure 9** indicate that different street environments have a significant effect on the level of activation of the quadriceps and gastrocnemius muscles. Higher %MVC values indicate increased muscle loading, which may lead to accelerated walking fatigue, while lower %MVC values indicate less muscle stress and more relaxed walking.

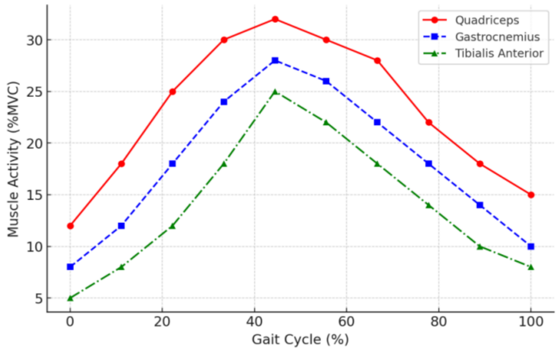

Figure 9. Trends in muscle activity (%MVC) over the walking cycle.

Table 12 shows the correlation between muscle activation levels and walking energy expenditure, and the data suggest that overactivation of the quadriceps and gastrocnemius muscles is usually associated with increased walking energy expenditure, and that a reasonable distribution of muscle loads can improve walking efficiency.

Table 12. Correlation between muscle activation levels and walking energy expenditure.

muscle group	%MVC (Maximum muscle power ratio)	Energy consumption (J/kg/m)
thigh muscles	32 ± 4.1	3.8 ± 0.5
gastrocnemius muscle	28 ± 3.5	3.5 ± 0.4
tibialis anterior muscle (anatomy)	25 ± 3.2	3.2 ± 0.4

Data source: analysis of activation levels and walking energy expenditure of different muscle groups based on EMG experimental data.

4.2.3. Traffic accident rate

Traffic accident rate is a key indicator of the safety of the street environment, especially in areas where pedestrians, cyclists and motorized vehicles intersect, and the accident rate is affected by the pedestrian flow, traffic flow, lighting conditions, and roadway facility layout. This study analyzes the frequency of pedestrian accidents, types of accidents, and their influencing factors based on historical traffic accident data in selected areas. The data sources include urban traffic management systems, video analysis from vehicle recorders and on-site observations, focusing on the occurrence of accidents at crosswalks, intersections, accessible passing lanes and carriageway intersections.

The frequency of pedestrian accidents is usually related to the traffic density ρ and the average walking speed v of road users. According to traffic flow theory, the probability of accident P_{acc} can be expressed as:

$$P_{acc} = \alpha \cdot \rho \cdot v \tag{13}$$

where α is the accident occurrence coefficient, which is influenced by the road environment and pedestrian behavior patterns. The data from the study in **Table 13** show that the risk of accidents increases significantly at pedestrian flow densities above 2.0 persons/m^2, mainly due to increased spatial interference between pedestrians and increased likelihood of accidental collisions due to decreased gait stability resulting from irregular roadway access.

Table 13. Accident rates at different pedestrian densities.

Pedestrian density (persons/m^2)	Accident rate (times/thousand persons/day)
0.5	0.8
1.0	1.5
1.5	3.2
2.0	5.0
2.5	7.8

Data source: Statistical analysis of accident records based on the Urban Traffic Management System.

The distribution of traffic accidents also varies significantly over time. **Figure 10** illustrates trends in accident frequency across time, and the data suggests that accident rates peak during the morning peak (7:00–9:00) and evening peak (17:00–19:00), consistent with variations in pedestrian density and motor vehicle traffic. In addition, accident rates are higher at night than during the day, suggesting that lighting conditions may have an impact on pedestrian recognition and access safety.

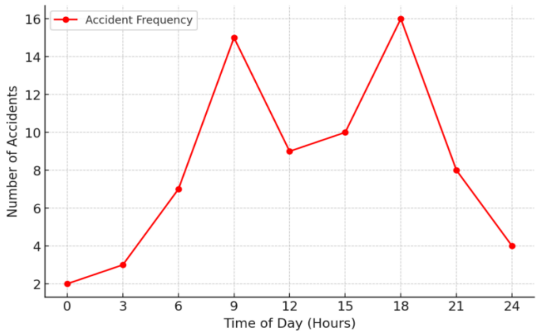

Figure 10. Frequency of traffic accidents in different time periods.

Table 14. Types of traffic accidents and percentage of occurrence.

Type of accident	Proportion of occurrences (%)
Pedestrian crossing accidents	35.2
Motor vehicle blind spot collisions	28.5
Non-Motorized Vehicle Collisions	18.6
Incidents of accessibility	10.3
Other accidents	7.4

Data source: Based on accident scene investigation and traffic surveillance data analysis.

Table 14, on the other hand, shows the percentage of different accident types. The data shows that pedestrian crossing accidents and motor vehicle blind spot collisions account for the highest percentage of accidents, suggesting that traffic safety at crosswalks and sidewalk intersections is a key factor in accident rates.

5. Conclusion

The core of street environment optimization is to improve the comfort, safety and health of pedestrians, and biomechanical analysis provides precise theoretical support. Factors such as gait, joint stress, muscle load, and traffic flow determine the rationality of street facilities. Based on systematic assessment, walking comfort, joint load and traffic safety are influenced by the environment. While the proposed biomechanical optimization strategies show significant promise for improving pedestrian health and safety, practical implementation may face challenges such as financial constraints, retrofitting existing infrastructure, and varying pedestrian needs across different urban contexts. Further research is necessary to address these challenges and explore the scalability of these strategies in diverse real-world settings.. Follow-up work needs to be combined with intelligent monitoring technology to achieve dynamic optimization of street facilities to adapt to the needs of different populations and improve the adaptability of urban space.

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