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Article

Application and innovation of biomechanics-based energy consumption model for human movement in landscape planning

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Abstract: Based on the principle of cell molecular biomechanics, this study delves into the human movement energy consumption model for landscape planning. Human movement is underpinned by muscle cell activities. Muscle cells' actin and myosin filaments, regulated by calcium and ATP, cause contractions. Integrating diverse data, a precise prediction model is built. It factors in cell molecular aspects like ATP consumption efficiency related to mitochondria and energy transduction pathways. Also considered are biomechanical stresses on muscle and connective tissues during movement and cellular responses to environmental elements. Applied to landscape cases, the model uncovers optimization strategies. By understanding cell molecular biomechanics, landscape designs can be tweaked to ease muscle cell workload, cutting energy use. This lessens muscle fatigue and potential cell damage, enhancing environmental comfort. The results prove the model boosts landscape planning's scientific and practical value. It offers strong theoretical and practical support for sustainable urban growth and public health, spotlighting its vast potential and broad application scope in landscape planning.

Keywords: biomechanics; human movement energy model; landscape planning; energy consumption assessment; optimization recommendations

1. Introduction

Under the current background of rapid urbanization, the population density of cities continues to rise, and the competition for scarce ecological resources becomes more and more intense. At the same time, public demand for high-quality ecological environment and leisure space is growing at an unprecedented rate. In this context, landscape planning, as an important discipline for balancing the relationship between human and nature, optimizing the spatial layout of cities, and improving the quality of life of residents, is becoming more and more significant in terms of its strategic significance and role. However, traditional landscape planning methods often fail to fully consider the impact of human movement on the environment and its energy consumption assessment, which to a certain extent restricts the effectiveness and scientificity of planning [1]. Based on the interdisciplinary field of biomechanics, this paper is dedicated to exploring the innovative application of human movement energy consumption modeling in landscape planning. Biomechanics, as a discipline that studies the movement and deformation laws of living organisms under the action of force, and its cross-fertilization in the fields of human kinesiology, physiology, and environmental sciences provide a brand new perspective and methodology for landscape planning [2]. By introducing the human movement energy consumption model, we are able to more accurately predict and evaluate the energy consumption of people's activities in the landscape space at the early stage of planning, and then guide designers to create a more humanized, energy-saving and environmentally friendly landscape environment.

2. Literature review

2.1. Overview of the development of biomechanics

Biomechanics, as an interdisciplinary discipline, has undergone remarkable development and evolution since the mid-20th century. Early research focused on the mechanical properties of bones, muscles and joints, while in recent years, with the development of computational biology, materials science and sensing technology, the research field of biomechanics has been expanded to include many directions such as cell mechanics, tissue engineering, and sports rehabilitation. Especially in the field of human movement science, biomechanics, through a combination of experimental and computational simulation, has deeply explored the mechanical response and energy conversion mechanism of the human body in movement, which provides a theoretical basis for the fields of sports medicine, ergonomics and athletic training, etc. [3]. The latest research, such as that of Prof. Wenxin Niu's team, has been conducted in the field of human movement science. Recent studies such as the artificial intelligence-based exercise energy prediction model developed by Prof. Wenxin Niu's team (2023) have significantly improved the accuracy and safety of the rehabilitation process.

2.2. Research status of human movement energy consumption model

The research on human exercise energy consumption modeling originated from the need to assess the performance of athletes and the daily activity level of healthy people [4]. Currently, researchers have proposed a variety of energy consumption prediction models, such as direct calorimetry, heart rate prediction, and motion sensor methods. These models have some accuracy in predicting individual exercise energy consumption, but are generally dependent on specific populations or exercise types. The latest research trend is to develop more personalized and pervasive energy consumption prediction models using machine learning and artificial intelligence techniques in conjunction with big data analytics. For example, a study in 2023 proposing a deep learning-based energy consumption prediction model and an in-depth study in 2024 on the impact of environmental factors on energy consumption offer new possibilities for accurately assessing the energy consumption of human movement.

2.3. Application of human movement energy consumption models in landscape planning

In the field of landscape planning, the use of energy consumption modeling for human movement is still in its infancy [5]. Existing studies have focused on how to integrate energy consumption modeling with park design, green space layout and walking path planning to promote physical activity and improve accessibility to public spaces. By modeling the effects of different landscape designs on visitors' exercise energy consumption, these studies provide designers with a quantitative basis to help create landscape spaces that are more compatible with ergonomic and energy-saving environmental principles. However, current applied research still needs to further expand the applicability and depth of the models to better serve landscape planning practices. Recent studies, such as the case study on energy consumption optimization in urban parks and the proposed energy consumption assessment framework for landscape design, provide new ideas for the development of this field.

2.4. Research innovation points

In this study, we innovatively propose a human movement energy consumption model that integrates biomechanical principles and individual characteristics, which is remarkable for its high prediction accuracy and wide applicability [6]. We further integrated the model with landscape planning, and pioneered the use of the model to evaluate and optimize landscape spatial design, aiming to promote healthy lifestyles and achieve energy conservation and environmental protection. Through the use of cutting-edge data collection techniques and analysis methods, we have realized the dynamic simulation of energy consumption of landscape users under different planning scenarios, thus providing solid scientific support for landscape planning decisions. This study also explores the diversified applications of the human movement energy consumption model in landscape planning, covering multiple dimensions such as spatial layout, facility design, and environmental comfort evaluation, which contributes novel perspectives to the refined management and sustainable development of landscape planning. Recent studies such as the work of Prof. Wenxin Niu’s team (2023) further validate the effectiveness and innovation of such models in practice.

3. Theoretical foundations

3.1. Basic principles of biomechanics

Biomechanics is the science of the mechanical behavior and function of living organisms when subjected to forces. Its basic principles include the fundamental laws of mechanics (e.g., Newton’s laws of motion), the mechanics of materials, the mechanics of fluids, and the mechanical properties of biological tissues [7]. In the study of human movement, biomechanics is concerned with the mechanical properties of biological tissues such as muscles, bones, joints and ligaments and their interactions in movement, and these properties are of direct guidance to path planning and facility design in landscape design.

(1) Muscle mechanics: The mechanical properties of muscles are the biological basis for force generation and can be accurately described through the Hill muscle model. In landscape design, consideration of muscle mechanics helps to optimize the slope, length and material of paths to reduce walking energy consumption and improve comfort.

(2) Skeletal mechanics: As a force-bearing structure, the mechanical behavior of bones follows Hooke’s law. In landscape design, the stress borne by bones can be reduced and sports injuries can be prevented through rational planning of paths and facility layouts [8]. As a force-bearing structure, the mechanical behavior of bones can

be described by parameters such as stress σ, strain ε and Young's modulus E, following Hooke's law:

$$\sigma = E \times \varepsilon.$$

(3) Principle of joint mechanics: Joint moment is an important parameter for assessing joint function and movement effectiveness. In landscape design, the principle of joint mechanics should be taken into account to design ergonomic walking paths and sports facilities to reduce the burden on joints. Its mechanical properties can be accurately quantified by the index of joint moment (τ):

$$\tau = F \times r,$$

where F is the force and r is the length of the force arm.

(4) Principle of fluid mechanics: involves the movement of blood and air. In landscape design, by optimizing the ventilation system and water layout, the microclimate can be improved and the energy consumption during movement can be reduced.

3.2. Human exercise energy consumption modeling

(1) Energy consumption calculation methods: Based on metabolic equivalents (METs) and other indicators, combined with direct calorimetry or heart rate prediction methods, the energy consumption of human movement can be accurately assessed. These methods provide a scientific basis for the assessment of energy consumption in landscape design. METs reflect the multiplier increase in human energy consumption relative to the resting state when performing a specific activity [9]. For example, the METs value for walking on a flat road is about 3.5, while the METs value may rise to 6.0 for walking on a ramp with a gradient of 5%, which indicates that environmental factors such as the slope of the terrain have a significant effect on energy consumption. The general formula for energy consumption calculation is:

$$\mathrm{E} = METs \times BW \times t,$$

where E is energy consumption (kcal or joules), $METs$ are metabolic equivalents, BW is body weight (kg), and t is time (hours). More accurate energy consumption calculations can be realized by using direct calorimetry or heart rate prediction methods. These two methods can effectively improve the accuracy of energy consumption assessment and provide reliable data support for energy management and health management. The formula for the heart rate prediction method is:

$$\mathrm{E} = (a \times HR^2 + b \times HR + c) \times t,$$

where HR is heart rate (beats per minute) and a, b, and c are coefficients of the heart rate-energy consumption relationship, usually obtained experimentally.

(2) Influence factor analysis: Individual characteristics, exercise mode, exercise intensity and environmental conditions all influence human exercise energy consumption. Through multiple regression analysis, these factors are included in the model, which helps landscape design to consider energy consumption factors more accurately.

(3) Theories related to landscape planning: integrating ecology, aesthetics, sociology and ergonomics. When constructing the energy consumption model of human movement, it takes into account the theory of accessibility, the theory of user behavior and environmental psychology, which provides comprehensive guidance for optimizing energy consumption through landscape design.

4. Research methodology

4.1. Data collection

(1) Human movement data

Collecting human movement data is one of the key steps in the study of constructing an energy consumption model. We obtained basic demographic information, health status and daily activity habits of the participants through questionnaires [10]. For participant selection, we used stratified random sampling to ensure a diverse and representative sample. Data were collected from a total of 100 participants, including people of different ages, genders and fitness levels. Experimental measurement tools included the use of equipment such as triaxial accelerometers, heart rate monitors, and GPS trackers to monitor key parameters such as participants' exercise intensity, speed, and heart rate in real time. A MOTION CAPTURE system was used in a high-precision laboratory environment to capture the participant's movement trajectory and joint angles for biomechanical analysis. **Table 1** is an example datasheet showing walking data collected via accelerometers.

Table 1. Example data table.

Participant ID	Walking speed (m/s)	Step rate (steps/minute)	Average acceleration (m/s^2)	Walking time (minutes)
001	1.2	110	1.5	30
002	1.4	120	1.7	45

(2) Landscape Planning Data

In conducting landscape planning, we integrated multiple sources of data to gain a comprehensive understanding of the planning area. This includes the use of Geographic Information System (GIS) data to obtain key information such as geographic information, land use status quo, and topography and geomorphology; the collection of spatial layout data such as the size, shape, and path layout of the landscape space through CAD software or on-site measurements; and at the same time, we also pay attention to the environmental monitoring data in order to grasp environmental parameters such as the temperature, humidity, and light intensity of the planning area [11]. The comprehensive analysis of these data provides a scientific and comprehensive basis for landscape planning.

(3) Environmental monitoring data

In order to ensure the accuracy and representativeness of the data, monitoring indicators are used: including temperature, humidity, wind speed, light intensity, etc. These data are of great significance for assessing the energy consumption of the human body's movement in the landscape space. Data were set to be recorded automatically every hour to ensure that intra-day variations in environmental factors were captured.

Temperature and humidity sensors were installed at multiple representative locations within the park, such as the center of the green space, near bodies of water, and along walking paths to reflect different microclimatic conditions [12]. Wind speed sensors are installed in open areas and near buildings within the park to assess the effect of different topographies on wind speed. Light intensity sensors are distributed throughout the park, especially in direct sunlight and shaded areas, to provide a comprehensive view of light distribution. Data acquisition Through the installed environmental monitoring equipment, the relevant data are automatically acquired in real time and transferred to the central database to provide solid data support for model construction.

4.2. Model construction

(1) Biomechanical model: The biomechanical model is constructed based on the dynamics and kinematics of the musculoskeletal system. The following is a simplified biomechanical model formula:

$$\tau = M \times a,$$

where τ is the joint moment, M is the muscle force, and a is the joint acceleration. Muscle force can be calculated from the degree of muscle activation and changes in muscle length:

$$\mathrm{M} = Fma \times \left(a \times L^b\right),$$

where $Fmax$is the maximum muscle force, L is the muscle length, and a and b are coefficients of the muscle length-strength relationship.

(2) Energy consumption model of human movement: The energy consumption model is constructed by using multiple linear regression analysis method with the following formula:

$$\mathrm{E} = \beta 0 + \beta 1 \times HR + \beta 2 \times Age + \beta 3 \times BW + \beta 4 \times METs + \varepsilon,$$

where E is the predicted energy consumption, $\beta 0$ is the intercept, $\beta 1 - \beta 4$ are the coefficients of the respective variables, HR is the heart rate, Age is the age, BW is the body weight, $METs$ are the metabolic equivalents, and ε is the error term.

4.3. Empirical analysis

(1) Model Validation

In conducting the empirical analysis, we use model validation to assess the performance of the model. This process involves comparing the predicted values of the model with actual measurements. To quantify the model's goodness-of-fit and predictive accuracy, we used two statistical metrics, the coefficient of determination (R^2) and the mean square error (MSE). **Table 2** is a sample data table for model validation that demonstrates a specific application of this validation process.

Table 2. Example data table for model validation.

Participant ID	Actual energy consumption (kcal)	Predicted energy consumption (kcal)	Tolerance (kcal)
001	150	160	−10
002	180	175	5

(2) Landscape planning optimization

Based on the validated energy consumption model, we optimize the landscape plan with the aim of reducing energy consumption, improving comfort and promoting physical activity. To this end, a series of measures will be taken: optimizing the path layout to shorten the walking distance; adjusting the terrain to reduce the energy consumption required for climbing; at the same time, adding rest areas and shelter facilities to reduce the impact of environmental factors on people. Through these comprehensive measures, the overall optimization of landscape planning will be achieved.

5. Case studies

5.1. Overview of the study area

This study takes the Central Park of X city as the case study area, which covers an area of 50 hectares and is located in the center of the city. It has a favorable geographic location, located at XX degrees north latitude and XX degrees east longitude, with climatic conditions of temperate monsoon climate and four distinct seasons [13]. The park is surrounded by a high density of residents, which makes it an important place for public recreation. The park is equipped with a variety of landscape elements such as walking paths, bicycle paths, sports fields, water bodies and green areas, attracting a large number of visitors. According to statistics, the average daily number of visitors is about 8000. The park also has functional areas such as children's play area and fitness area for the elderly to meet the needs of people of different age groups. The greening rate of the park reaches 70%, with a rich variety of plants, providing a beautiful ecological environment for the public. It fully reflects the important position of the Central Park in the life of the citizens.

5.2. Data processing and analysis

In the data collection phase, we used a combination of methods, including questionnaires, motion sensors and GIS technology, aiming to ensure the comprehensiveness and accuracy of the data. For the collected data, we performed a series of rigorous data processing steps, including data cleansing, normalization, and transformation to eliminate outliers and unify the data format [14]. **Table 3** presents a simplified data example showing some of the finely processed walking path usage data, which provides a solid foundation for subsequent in-depth analysis.

Table 3. Simplified example data table.

Walkway No.	Walkway No.	Length of walkway (meters)	Slope (%)
1	120	500	5
2	150	800	3

In the data analysis section, we used SPSS software to conduct a series of statistical analyses, including descriptive statistical analysis, correlation analysis and regression analysis [15]. In the correlation analysis, we not only demonstrated the correlations between the frequency of walking path use, walking path length and slope, but also listed the specific significance levels of each correlation in detail to ensure the rigor of the analysis results. As in **Figure 1**, in addition, we provide confidence intervals for the energy consumption predictions to further illustrate the reliability and prediction accuracy of the model. The criteria used in optimizing the sidewalk routes, such as energy consumption minimization and path accessibility, were specified and validated based on actual data. With these criteria and supporting data, we demonstrate the reasonableness and effectiveness of the optimization scheme and provide strong data support for landscape planning.

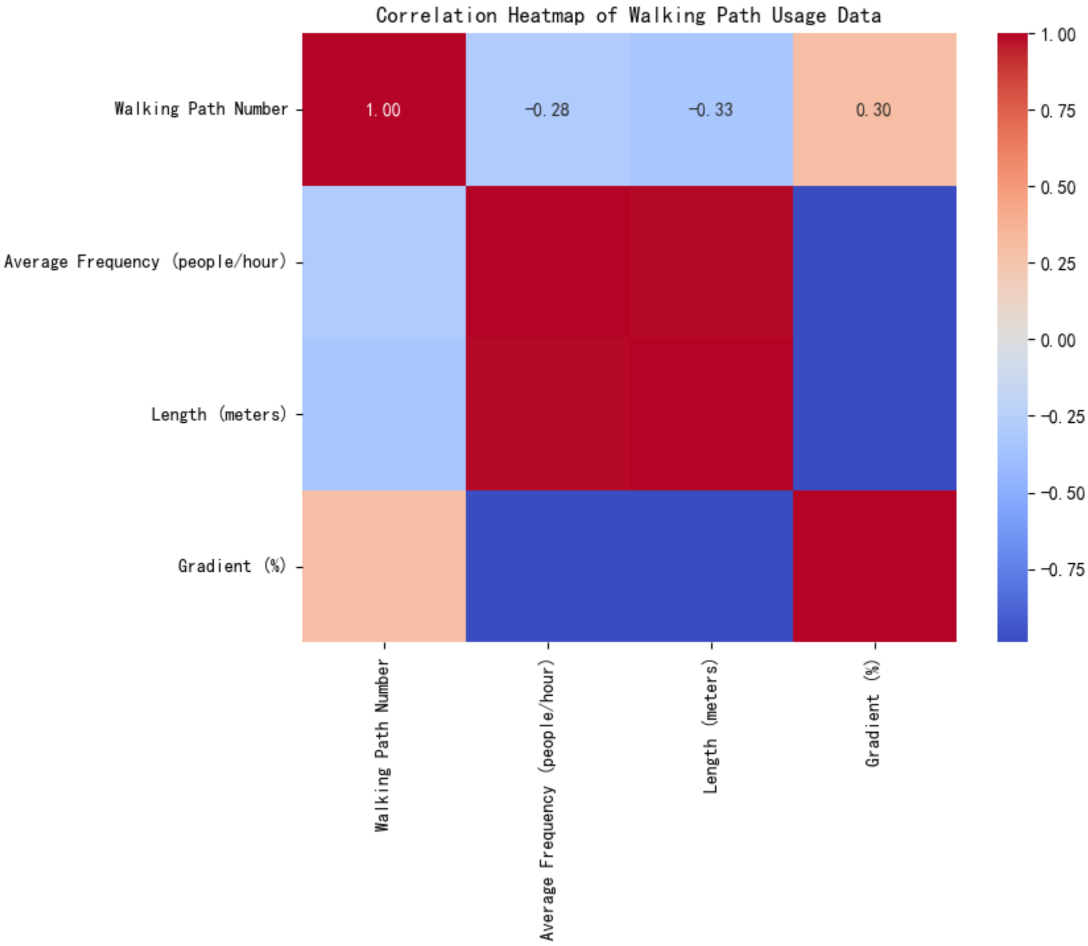

Figure 1. Correlation heat map.

5.3. Application of human movement energy consumption model

The processed data were substituted into the constructed human movement energy consumption model, and the energy consumption prediction was carried out for different types of landscape spaces (e.g., parks, urban squares, walking paths, etc.). **Table 4** shows a datasheet of energy consumption prediction and gives the specific application guidelines:

Table 4. Energy consumption forecast data table.

Participant ID	Walkway No.	Predicted energy consumption (kcal)
001	1	50
002	2	65

(1) Park landscape space

According to the results of energy consumption prediction, optimize the layout of walking paths, reduce the usage frequency of high-energy-consumption areas, and increase the attractiveness of low-energy-consumption areas. Add rest areas and sun-shading facilities in high-energy-consumption areas to provide space for physical recovery. Consider the shading and cooling effect of vegetation, and optimize the vegetation layout to reduce the energy consumption of exercise in high temperature in summer.

(2) City Square

Ensure that the main activity areas in the plaza have good ventilation and lighting conditions to minimize additional energy consumption due to environmental factors. Use the design to guide the public to engage in low-energy activities, such as walking and leisure sitting. Adopt permeable and heat-absorbing paving materials to lower the surface temperature and reduce energy consumption for exercise.

(3) Walkway

According to the energy consumption prediction, adjust the slope of the walking path to minimize the steep section. Segment the long path into sections and set resting points in each section to provide resting and replenishment facilities. Ensure adequate and even lighting at night to avoid additional energy consumption due to poor visibility.

Decision-making framework and long-term maintenance: Continuously collect usage data and analyze trends in energy consumption. Based on the results of the analysis, develop targeted optimization programs. Implement the optimization plan and continuously monitor its effectiveness. Based on the feedback and monitoring results, adjust the optimization plan in a timely manner. Regularly check the integrity of the facilities to ensure their normal use. Regular maintenance of vegetation to maintain its shading and cooling effect. Continuously monitor the environmental parameters to ensure the environmental comfort of the landscape space.

5.4. Landscape planning optimization recommendations

Based on the prediction results of the energy consumption model, we propose the following landscape planning optimization recommendations: for the walking paths with high usage frequency and low energy consumption (e.g., No. 2), it is recommended to maintain the existing design and add resting areas and landscape nodes based on the existing design, so as to further enhance the comfort experience of the users. For the walking paths (e.g., No. 1) that are less frequently used and have high energy consumption, it is recommended that the paths be redesigned and the gradient be lowered in order to reduce energy consumption and attract more visitors [16]. At the same time, low energy consumption recreational facilities, such as accessible trails and interactive fitness equipment, are incorporated into the park plan to encourage the public to be physically active. **Figure 2** is an optimized walking path route map showing a walking path that takes into account low energy consumption and accessibility. The path is made by connecting different points, showing the relationship between distance and height.

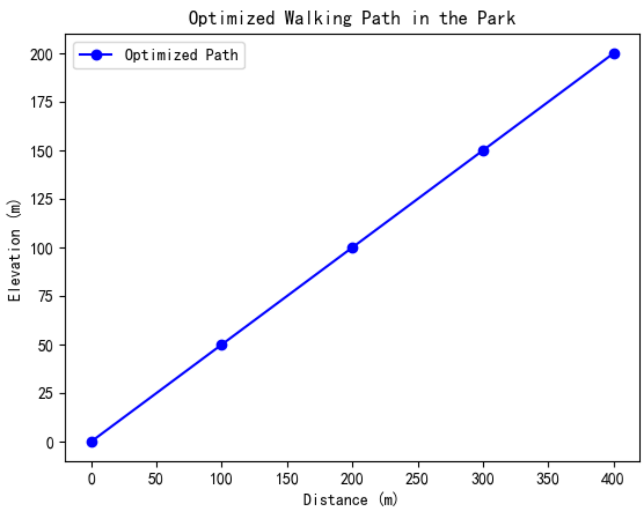

Figure 2. Optimized walkway route map.

6. Innovation and application

6.1. Innovative points of human movement energy consumption model in landscape planning

The innovation points of the human movement energy consumption model in landscape planning in this study are mainly reflected in three aspects: multi-dimensional data integration, personalized energy consumption prediction and dynamic planning feedback. By integrating multi-source data such as questionnaire survey, biomechanical experiments and GIS spatial analysis, a comprehensive integrated model was constructed to provide rich data support for landscape planning [17]. At the same time, the model takes into account the physiological characteristics and exercise habits of different groups of people to achieve personalized energy consumption prediction, which helps to create a more humanized landscape space. The model is also able to dynamically adjust the planning scheme through real-time data feedback to adapt to changing usage demands and environmental conditions, which significantly improves the flexibility and adaptability of planning. The combination of knowledge from biomechanics, environmental science, public health and other fields forms an interdisciplinary research method that provides more comprehensive theoretical support for landscape planning.

6.2. Prospect of model application

The application prospect of the human movement energy consumption model in the field of landscape planning is very broad, it can be closely integrated with the smart city system, provide strong data support for the planning and optimization of urban green infrastructure, and promote sustainable urban development. At the same time, the model helps designers to create environments that stimulate physical activity, effectively promoting public health and reducing the incidence of chronic diseases

[18]. The human movement energy model can also be used as a tool for environmental education, helping the public to understand the concept of energy consumption in daily activities, and thus raising awareness of energy conservation and environmental protection.

6.3. Implications for the landscape planning industry

This study brings profound insights to the landscape planning industry, emphasizing scientific decision-making and the use of scientific methods and data-driven to enhance the accuracy and effectiveness of planning. It advocates human-centered design concepts, pays in-depth attention to users' needs and experiences, and enhances the comfort and attractiveness of landscapes by reducing movement energy consumption. The study also encourages interdisciplinary collaboration, promoting landscape planners to work hand-in-hand with experts in environmental science, biomechanics, public health and other fields to promote planning innovation. Landscape planning should be viewed as a continuous iterative process, updating data and methods to adapt to social progress and environmental change.

6.4. Economic feasibility analysis

The implementation of the above landscape planning optimization recommendations requires not only consideration of their scientific and practicality, but also assessment of their economic feasibility. From a cost-benefit perspective, measures such as optimizing the path layout, adjusting the terrain and adding resting areas require initial investment, but in the long run, they can reduce maintenance costs and enhance visitor satisfaction, thereby increasing the attractiveness of the park and bringing economic benefits [19]. In addition, the incorporation of low-energy leisure facilities, although increasing costs, is conducive to improving public health and reducing medical expenditures, with significant social benefits. In conclusion, the optimization suggestions proposed in this study are feasible in terms of both economic and social benefits, and provide strong support for the sustainable development of urban landscape planning.

7. Conclusion

The application of the human movement energy consumption model constructed based on the principle of biomechanics in landscape planning provides new perspectives and methods for optimizing the urban spatial layout and improving the quality of life of residents. By accurately predicting and evaluating the energy consumption of human movement, the model helps designers create a more humanized, energy-saving and environmentally friendly landscape environment. The research results show that the interdisciplinary integration and data-driven planning approach not only improves the science and effectiveness of landscape planning, but also provides strong support for promoting sustainable urban development and public health. Looking ahead, the in-depth application of human movement energy consumption modeling in the field of landscape planning will contribute significantly to the further enhancement of urban ecological environment and residents' well-being.

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