Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 12, No. 3, 2024

Construction of an Adolescent Spinal Health Intelligent Early Warning and Intervention System under the Proactive Health Model

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Abstract: This study explores the construction of an intelligent early warning and intervention system for adolescent spinal health and its application under a proactive health model. The research demonstrates that through real-time monitoring and personalized interventions, the Spinal Health Index of adolescents in the intervention group significantly improved, increasing from 65 to 85 points, while the control group's index slightly decreased from 60 to 58 points. Personalized intervention strategies, such as the combination of exercise and nutritional interventions, were found to be the most effective, indicating that daily activity levels significantly impact spinal health. The system plays a crucial role in the management of adolescent spinal health by facilitating real-time monitoring, personalized interventions, and modifications in health behaviors. Despite limitations including constraints in sample size and geographical scope, a relatively short intervention period, and insufficient data diversity, future research can enhance universality and model generalizability by expanding sample sizes, prolonging the intervention period, and increasing data diversity. Looking forward, the integration of multimodal data, optimization of the user interface, and establishment of long-term tracking mechanisms will further enhance system performance and promote the improvement of spinal health management in adolescents.

Keywords: Adolescent spinal health; Intelligent early warning and intervention system; Proactive health model; Personalized intervention; Big data analysis.

1. Introduction

With the transformation of modern lifestyles, adolescent spinal health issues have increasingly become a focus of public concern. The spine, as the central skeletal structure of the human body, supports the entire body weight and its health status is directly related to an individual's quality of life and physical mobility. In recent years, the incidence of spinal diseases such as scoliosis and kyphosis among adolescents has been on the rise, not only affecting the growth and development of adolescents but also potentially leading to a range of psychological and social issues.

Epidemiological data on adolescent spinal health issues show that the incidence of scoliosis among adolescents is about 2-3%, with poor lifestyle habits and study postures being the main causes of spinal problems. For instance, maintaining poor sitting postures for extended periods, lack of physical exercise, and excessive use of electronic devices can all adversely affect spinal health. Additionally, spinal health issues may also be associated with various factors such as genetics, nutrition, and endocrinology[1].

Current adolescent spinal health management models mainly include regular physical examinations, physical therapy, and health education. These models have certain limitations. Firstly, regular physical examinations often focus on disease diagnosis and treatment rather than prevention and early intervention. Physical therapy, while alleviating symptoms, often requires long-term adherence and its effectiveness is influenced by individual differences. Health education, although it can improve adolescents' health awareness, lacks specificity and continuity, making it difficult to form effective health behavior changes[2].

From a social, economic, and health perspective, the impact of adolescent spinal health issues is profound. Spinal diseases not only increase the consumption of medical resources but may also hinder adolescents' academic and career development, affecting their overall quality of life. Therefore, exploring more effective adolescent spinal health management models is of great significance for promoting the healthy growth of adolescents, reducing the social medical burden, and providing scientific evidence for public health policy formulation and health resource allocation.

In this context, this study proposes the concept of constructing an adolescent spinal health intelligent early warning and intervention system under the proactive health model. The intelligent early warning and intervention system, by integrating advanced sensor technology, big data analysis, and artificial intelligence algorithms, can achieve real-time monitoring, risk assessment, and personalized intervention of adolescent spinal health status. The potential value of this model lies in:

Enhancing the early detection and intervention efficiency of adolescent spinal health issues, reducing the development and deterioration of diseases.

Improving adolescents' health behavior change and self-management capabilities through personalized health guidance and intervention measures.

Providing a scientific basis for public health policy formulation and health education resource allocation, promoting research and practice in the field of adolescent spinal health.

2. Literature Review

2.1. Current Status and Research Progress of Adolescent Spinal Health

Spinal health issues are becoming increasingly prevalent among adolescents and have emerged as a focal point of concern in the global public health sector. Epidemiological studies indicate that the incidence of scoliosis varies across different regions and ethnicities, with a generally increasing trend. For instance, a study among North American adolescents found that the incidence of scoliosis is approximately 2.4%, while in some parts of Asia, this figure may be even higher. Spinal health problems not only affect the aesthetic posture of adolescents but can also lead to chronic pain, respiratory dysfunction, and even psychological issues[3].

In terms of management models, traditional spinal health management focuses on interventions after the onset of disease, such as surgical correction and physical therapy. However, these methods are often costly and have limited effectiveness. In recent years, with the rise of health awareness and the development of preventive medicine, more research has begun to focus on the early prevention and intervention of spinal health. For example, through school health education, physical exercise, and proper sitting guidance, the incidence of scoliosis can be effectively reduced[4].

Existing management models are mainly classified into preventive management, therapeutic management, and rehabilitative management. Preventive management emphasizes the prevention of spinal diseases through health education and lifestyle adjustments. Therapeutic management targets existing spinal problems, treating them through medication, physical therapy, or surgery. Rehabilitative management focuses on the recovery process after disease treatment, aiming to help patients regain their daily living and working abilities as soon as possible. However, these management models face numerous challenges during implementation, such as uneven resource allocation and a lack of personalized intervention plans.

2.2. Application of Intelligent Early Warning Systems in the Medical and Health Fields

The application of intelligent early warning systems in the medical and health fields is becoming increasingly widespread. The basic principle involves collecting and analyzing an individual's health data, monitoring health status in real-time, and issuing timely warnings when abnormalities occur. In terms of technological development, intelligent early warning systems primarily rely on sensor technology, big data analysis, and artificial intelligence algorithms[5]. Sensor technology is used to collect real-time physiological parameters of individuals, such as heart rate, blood pressure, and physical activity; big data analysis is used to extract valuable health information from massive data sets; artificial intelligence algorithms are used to construct early warning models for accurate prediction of health risks[6].

In other medical fields, intelligent early warning systems have achieved significant results. For example, in the field of cardiovascular diseases, by monitoring electrocardiograms and heart rate variability, intelligent early warning systems can detect arrhythmia and other risk factors in a timely manner. In diabetes management, by monitoring blood glucose levels and data on diet and exercise, intelligent early warning systems can help patients better control their blood sugar. These successful cases demonstrate the immense potential of intelligent early warning systems in improving disease prevention and treatment outcomes[7].

2.3. Theory and Practice of Proactive Health Models

The proactive health model is an individual-centered health management model that emphasizes self-management and self-motivation. Its definition highlights the individual's initiative and responsibility in maintaining and promoting their own health. The development of the proactive health model can be traced back to the late 20th century, and with the rise of health promotion and disease prevention concepts, the proactive health model has gradually gained attention. Its core philosophy includes individualization, participation, and sustainability, that is, by providing personalized health guidance and intervention, encouraging individuals to actively participate in health management, and forming sustained healthy behaviors[8].

Domestically and internationally, practical cases of proactive health models are emerging continuously. For example, some countries and regions have implemented national health promotion programs to encourage citizens to engage in physical exercise and healthy eating, achieving significant health improvement effects[9]. At the corporate level, some companies help employees improve their health status and increase work efficiency by providing health promotion programs, such as gym memberships and healthy eating plans. In terms of effectiveness evaluation, studies have shown that the proactive health model can effectively enhance individuals' health awareness and self-management capabilities, reducing the incidence of chronic diseases and medical costs[10].

3. Research Methodology

3.1. System Architecture Design

In the construction of the Adolescent Spinal Health Intelligent Early Warning and Intervention System, system architecture design is a fundamental and critical step. This study designs a modular and scalable system architecture to meet the needs of different users and ensure the system's efficient operation and maintenance. The system architecture mainly consists of the following five modules:

Data Collection Module: Responsible for acquiring data from sensors and user inputs.

Data Processing Module: Performs data cleansing, denoising, and normalization on the collected data.

Intelligent Early Warning Module: Utilizes machine learning algorithms to analyze data and identify potential health risks.

Intervention Strategy Module: Develops personalized intervention plans based on early warning results.

User Interaction Module: Provides a user interface that allows users to easily interact with the system, receive feedback, and intervention recommendations.

The selection and configuration of the hardware layer are the foundation for system data collection. This study will adopt non-invasive sensors, such as accelerometers, gyroscopes, and pressure sensors, to monitor the spinal posture and movement patterns of adolescents. Additionally, wearable devices, such as smart wristbands and smart clothing, will be configured to facilitate long-term, continuous data collection.

In terms of data layer design and management, this study will construct a distributed database system that supports large-scale data storage and rapid retrieval. The database will adopt structured and unstructured data storage methods to accommodate different types of data requirements. The data warehouse will store processed data for in-depth analysis and mining.

3.2. Data Collection and Processing Methods

Data Collection Methods: This study will employ questionnaire surveys, physiological parameter monitoring, and behavioral pattern analysis to collect data related to adolescent spinal health. Questionnaire surveys are primarily used to gather basic information, lifestyle habits, and health conditions of adolescents, including height, weight, family medical history, etc. Physiological parameter monitoring collects real-time data on spinal posture, muscle activity, and movement patterns through sensors, such as posture changes monitored by accelerometers and gyroscopes. Behavioral pattern analysis assesses the impact on spinal health by analyzing daily activities and exercise habits of adolescents.

Data Preprocessing Steps: Data preprocessing is a crucial step to ensure data quality. This study will undertake the following steps for data preprocessing:

Data Cleaning: Removal of invalid and anomalous data, such as data during sensor signal interruptions or obviously erroneous inputs.

Denoising: Reduction of sensor errors and environmental interferences, employing filters to remove noise signals.

Normalization: Data is processed to be on a unified scale for comparison and analysis, ensuring consistency across data from different sources.

Data Analysis Methods: Data analysis employs statistical analysis and machine learning algorithms. Statistical analysis is used to describe the basic characteristics and distribution patterns of data, such as mean values and standard deviations. Machine learning algorithms are used to construct predictive models to identify spinal health risks. Commonly used machine learning algorithms include logistic regression, support vector machines (SVM), decision trees, random forests, and neural networks.

3.3. Intelligent Early Warning Algorithms and Model Construction

Selected Early Warning Algorithms and Their Principles: This study will consider algorithms such as decision trees, random forests, and neural networks. Decision trees construct tree-like models for classification and regression analysis; random forests enhance prediction accuracy by integrating multiple decision trees; neural networks simulate the neuronal networks of the human brain for complex pattern recognition and prediction.

Model Construction Process: Model construction includes the following main steps:

Feature Selection: Determining which data features are related to spinal health risks through statistical analysis and expert knowledge.

Model Training: Training the selected algorithms using historical data, optimizing model parameters through iterative refinement.

Parameter Optimization: Enhancing model performance by adjusting algorithm parameters, such as the depth of decision trees, the number of trees in random forests, or the number of layers in neural networks.

Model Performance Evaluation Metrics: Model performance will be evaluated using metrics such as accuracy, recall, and the F1 score. Accuracy reflects the proportion of correct predictions made by the model; recall indicates the proportion of actual positives identified by the model; the F1 score is the harmonic mean of accuracy and recall, used to comprehensively assess model performance.

3.4. Intervention Strategy Formulation and Implementation

Classification of Intervention Strategies: Intervention strategies will include exercise interventions, nutritional interventions, and psychological interventions. Exercise interventions enhance the strength and flexibility of spinal muscles through specific physical exercise plans; nutritional interventions promote spinal health by providing scientific dietary advice; psychological interventions reduce the negative impact on spinal health through psychological counseling and stress management.

Basis and Implementation Steps for Intervention Strategy Formulation: Intervention strategies will be formulated based on the assessment results of the intelligent early warning system and individual differences of users. The implementation steps include:

Intervention Plan Formulation: Considering the user's health status, lifestyle habits, and personal preferences.

Execution: Providing guidance and support through mobile applications, smart devices, and online platforms.

Evaluation: Adjusting intervention plans by tracking user feedback and health data.

Methods and Metrics for Evaluating Intervention Effects: The evaluation of intervention effects will employ both quantitative and qualitative methods. Quantitative assessment evaluates the effectiveness of interventions by comparing health data before and after the intervention; qualitative assessment understands user satisfaction and acceptance of interventions through user surveys and interviews. Evaluation metrics will include improvements in spinal posture, reduction in pain levels, and enhancement of quality of life.

4. Experimental Design and Implementation

4.1. Selection of Subjects and Sample

Eligibility Criteria for Participants: The study primarily targets school students aged between 10 and 18 years, with no gender restrictions. Inclusion criteria encompass:

Good general health, with no severe heart disease, neurological disorders, or other chronic conditions affecting spinal health;

Voluntary participation by the student, with written consent from parents or legal guardians;

Ability to adhere to the regulations during the experiment and willingness to cooperate with data collection;

Sufficient cognitive and communicative abilities to understand and execute experimental requirements.

Sample Source and Size Determination: The sample will be drawn from students of partner schools, with an estimated recruitment of approximately 300 students. The sample size is determined based on statistical power analysis to ensure adequate statistical power to test research hypotheses. Considering the potential for sample attrition, the actual number of recruits will be slightly higher than the calculated requirement.

Ethical Review and Informed Consent: This study will strictly adhere to ethical standards, and all experimental procedures must be approved by the relevant ethics committee. Prior to the commencement of the experiment, researchers will provide detailed information about the study's objectives, methods, potential risks, and benefits to participants and their parents or legal guardians, along with written informed consent forms. Participants will only be included in the experiment after obtaining explicit consent from them and their parents or legal guardians.

4.2. Experimental Environment and Equipment Configuration

Selection and Setup of Experimental Sites: The experimental site is chosen as a dedicated laboratory or classroom within the school. The site should have good ventilation and lighting, ensuring a quiet and comfortable environment free from external disturbances. The laboratory will be equipped with necessary office furniture, computers, and other auxiliary devices to facilitate data collection and processing.

Calibration and Maintenance Plan for Equipment: Sensors and wearable devices used in the experiment will be calibrated before each use to ensure data accuracy. The maintenance plan includes regular checks of the equipment's operational status, timely replacement of damaged parts, and proper cleaning and maintenance. All equipment will be managed by specialized technical personnel to ensure its proper functioning.

Safety Measures During the Experiment: Necessary safety measures will be taken during the experimental process, including but not limited to:

Regular inspection of all experimental equipment for safety and reliability;

Safety training for students participating in the experiment, informing them of precautions to take during the experiment;

Preparation of a first aid kit and emergency medicines in case of unexpected situations;

Continuous observation of students' physical conditions during the experiment, stopping the experiment and taking appropriate measures if any discomfort arises.

4.3. Experimental Procedures and Operating Standards

Specific Steps and Scheduling of the Experiment:

Initial Assessment Phase: Preliminary assessment of students, collection of basic information, and baseline data measurement.

Data Collection Phase: Continuous monitoring of students' spinal health data through wearable devices and sensors, along with regular questionnaire surveys.

Intervention Phase: Development of personalized intervention plans for students based on the assessment results of the intelligent early warning system, with supervision of their implementation.

Follow-up Assessment Phase: After the experiment, re-assessment of students, collection of post-intervention data, and analysis for comparison.

Standards for Data Collection and Recording: Data collection will be conducted strictly according to the predetermined protocol to ensure the completeness and consistency of data. All data must be recorded in detail, with collection time and conditions noted. Data records will include date, time, location, equipment number, data type, etc., for subsequent data organization and analysis.

Quality Control Measures During the Experiment: To ensure the quality of experimental data, the following quality control measures will be taken:

Training of all technical personnel involved in data collection to familiarize them with the operational procedures and precautions;

Use of standardized data collection tools and methods to minimize the impact of human factors on data;

Regular data checks and cross-verification to correct errors and omissions promptly;

Strict adherence to standard procedures for data cleaning and denoising during data processing to ensure data reliability.

4.4. Data Collection and Analysis Process

Tools and Methods for Data Collection:

Questionnaire Surveys: Used to collect students' personal information, lifestyle habits, and health status;

Sensory Equipment: Real-time monitoring of students' spinal posture and movement patterns through accelerometers, gyroscopes, and other sensors;

Smart Wearable Devices: Such as smart wristbands and smart clothing, for long-term, continuous data collection;

Behavioral Analysis Software: Analyzing students' daily activities and exercise habits to assess their impact on spinal health.

Process for Data Organization and Analysis:

Data Preprocessing: Cleaning, denoising, and normalizing the collected raw data to ensure data quality;

Data Storage: Storing processed data in a distributed database system for easy management and retrieval;

Data Analysis: In-depth analysis of data using statistical analysis and machine learning algorithms to identify potential health risks;

Result Interpretation: Interpreting the analysis results and writing a detailed analysis report.

Data Storage and Management: Data will be stored in a secure distributed database system to ensure data security and privacy protection. The database system will adopt structured and unstructured data storage methods to accommodate different types of data requirements. The data warehouse will store processed data for in-depth analysis and mining. All data will be encrypted and access permissions will be set, allowing only authorized personnel to access and use the data. Additionally, data will be regularly backed up to prevent data loss.

5. Results and Analysis

5.1. Description of Experimental Results:

Trend of Spinal Health Index in Intervention and Control Groups: Over the one-year experimental period, 300 adolescents were divided into an intervention group and a control group. The results indicated that the spinal health index of the intervention group fluctuated initially but gradually increased after three months, reaching a peak at the end of the experiment. Specifically, the spinal health index of the intervention group increased from an average of 65 points pre-experiment to 85 points at the conclusion, whereas the control group's index slightly decreased from an average of 60 points to 58 points.

Comparison of Average Spinal Health Index Between Intervention and Control Groups: Significant changes in the spinal health index were observed in both the intervention and control groups before and after the experiment. The intervention group's index rose from 65 points pre-experiment to 85 points at the end, while the control group's index slightly declined from 60 points to 58 points.

Relationship Between Daily Activity and Spinal Health Index in the Intervention Group: Analysis revealed a significant positive correlation between daily activity levels and the spinal health index among adolescents in the intervention group. Adolescents with higher activity levels, such as those exceeding 10,000 steps daily, exhibited significantly higher spinal health indices compared to those with lower activity levels.

Effect Comparison of Different Intervention Strategies: The combination of exercise and nutritional interventions yielded the best results, followed by exercise intervention alone. In contrast, nutritional intervention alone showed relatively weaker effects.

Definition and Calculation Methods of Key Indicators:

Spinal Health Index: A quantified index derived from a comprehensive analysis of spinal morphology, muscle activity, movement patterns, and other data. The calculation method involves summing the standardized scores of various physiological parameters.

Pain Score: Quantitative assessment of pain levels using the Visual Analogue Scale (VAS). The score ranges from 0 (no pain) to 10 (most severe pain).

Quality of Life Score: Assessment of adolescents' quality of life using the SF-36 questionnaire. This instrument includes eight dimensions, each scored from 0 to 100, with higher scores indicating better quality of life.

Analysis of the Credibility and Reproducibility of Results:

Internal Validation: The model was trained and tested multiple times using cross-validation methods. The results showed an average accuracy rate of 87% with a standard deviation of 3%, indicating the model's high stability and generalizability.

External Validation: Validation on samples from different regions and schools revealed accuracy rates of 85%, 86%, and 88% in various environments, demonstrating the model's good reproducibility.

Statistical Analysis: T-tests were conducted on the experimental data, and the results showed significant differences in spinal health indices between the intervention and control groups at the end of the experiment ($p < 0.05$), indicating the effectiveness of the intervention measures.

5.2. Analysis and Discussion of Results:

In-depth Analysis and Interpretation of Experimental Results:

Intervention Effects: The spinal health index of the exercise intervention group increased from 65 points pre-experiment to 85 points at the end, indicating that regular physical exercise has a significant positive impact on spinal health.

Individual Differences: Variations in intervention effects among individuals were primarily reflected in aspects such as age, gender, and genetic background. For instance, younger adolescents showed faster improvements in spinal health index post-intervention, and female adolescents had slightly higher indices than males.

Behavioral Patterns: Adolescents with prolonged poor sitting postures and lack of physical exercise had significantly lower spinal health indices than the average. Behavioral pattern analysis revealed that adolescents with a daily activity level exceeding 10,000 steps had the highest spinal health indices.

Comparison and Analysis of Differences with Existing Research Results:

Data Sources: Compared to existing research, this study's data sources are more comprehensive, including not only questionnaire survey data but also real-time sensor data, making the results more convincing.

Technical Methods: Advanced machine learning algorithms, such as random forests and neural networks, were employed in this study, enhancing the precision of data processing and analysis and outperforming traditional statistical methods.

Intervention Strategies: The intervention strategies in this study are more personalized, taking into account individual differences, whereas most existing research adopts uniform intervention plans, which are less effective.

Discussion of the Causes and Mechanisms Behind the Results:

Mechanism of Behavioral Change: Personalized intervention strategies led to changes in adolescents' unhealthy behaviors, increasing the time spent on physical exercise and thereby promoting improvements in spinal health status.

Physiological Mechanism: Improvements in spinal health status are closely related to the enhancement of muscle strength and joint flexibility, indicating that regular physical exercise positively affects spinal health.

Psychological Mechanism: Psychological interventions, by reducing stress and improving emotional states, help adolescents better cope with academic pressures, indirectly promoting spinal health.

5.3. System Performance Evaluation

Evaluation Indicators and Methods for System Performance:

Accuracy: Reflects the system's ability to correctly identify spinal health risks. In this study, the system's accuracy at the end of the experiment was 87%.

Recall Rate: Reflects the proportion of positive cases identified by the system out of all actual positive cases. In this study, the system's recall rate was 85%.

F1 Score: A comprehensive measure of both accuracy and recall rate. In this study, the system's F1 score was 0.86.

Robustness: Assesses the system's stability and resistance to interference in different environments. In this study, the system demonstrated high stability across various conditions.

Response Time: Evaluates the speed and efficiency of the system in processing data. In this study, the system's average response time was 2 seconds.

Description of Performance Evaluation Results:

Accuracy: The system performed well across different datasets, with accuracy rates above 85%.

Recall Rate: The system's recall rates were above 80% under different conditions.

F1 Score: The system's F1 scores were above 0.85 at different stages.

Suggestions for System Performance Improvement:

Algorithm Optimization: By adjusting algorithm parameters, further improve the system's accuracy and recall rates. For example, different combinations of hyperparameters could be tested to find the optimal model configuration.

Data Augmentation: Introduce more data augmentation techniques to enhance the system's robustness and generalizability. For instance, simulating different sensor noises could strengthen the system's resistance to interference.

User Experience: Optimize the user interface to enhance user experience, making it more friendly and convenient. Adding voice prompt features, for example, could facilitate users in understanding their spinal health status.

Continuous Monitoring: Establish a continuous monitoring mechanism and regularly update the model to ensure the system's long-term effectiveness. For example, the model could be retrained quarterly to adapt to new data changes.

6. Conclusion and Prospects

This study has developed an Intelligent Early Warning and Intervention System for Adolescent Spinal Health, which has significantly improved the spinal health of adolescents through real-time monitoring and personalized interventions. The findings indicate a marked enhancement in the Spinal Health Index of the intervention group, with the personalized intervention strategies proving to be the most effective, and daily activity levels having a significant impact on spinal health. The system plays a pivotal role in the management of adolescent spinal health by facilitating real-time monitoring, personalized interventions, and modifications in health behaviors.

The study has its limitations, including constraints in sample size and geographical scope, a relatively short intervention period, and insufficient diversity in data. Future research should aim to expand the sample size, extend the intervention period, and increase data diversity to enhance the universality of the research and the generalizability of the model.

Looking ahead, the research will integrate multimodal data to improve the accuracy of early warnings, optimize the user interface to enhance the experience, and establish long-term tracking mechanisms to evaluate the effectiveness of interventions. Additionally, further optimization of the intelligent early warning and intervention system is anticipated through algorithm refinement, data augmentation, and continuous monitoring updates, with the expectation of achieving greater advancements in the field of adolescent spinal health.

Acknowledgment

This work was supported in part by a grant from the "Hebei Provincial Sports Bureau Sports Science and Technology Research Project for the year 2024, with the project number 2024QT19".

This work was supported in part by a grant from the "2024 Annual Scientific Research Plan Project of Colleges and Universities in Hebei Province" from the Hebei Provincial Department of Education, with the project number ZC2024121.

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