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Optimization Design of Operational Postures for Intelligent Warehouse Pickers - An Empirical Study Based on Human Factors Engineering

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Abstract **Original Research Article**

Against the backdrop of the rapid development of e-commerce logistics, human factor efficiency issues in the order picking of intelligent warehouses have become increasingly prominent. This study takes intelligent warehouse centers in Chengdu as research objects, based on the theoretical framework of human factors engineering, and conducts in-depth analysis of key problems in pickers' operational postures through systematic literature research and on-site empirical investigations. It proposes a dual-dimensional solution integrating shelf system optimization and intelligent tool integration. The research finds that bending movements account for 33% of existing picking processes, leading to a high incidence of occupational injuries such as lumbar muscle strain reaching 67%. The core reasons include unreasonable shelf heights, insufficient tool adaptability, and redundant operational processes. Through the comprehensive application of golden working zone planning, lifting picking trolleys, and gesture control technology, it is expected to reduce bending movements by 50% and improve operational efficiency by nearly 20%. This provides a replicable practical path for human factor optimization in intelligent warehouses. The research results not only have practical significance for reducing occupational injury risks but also enrich the application paradigm of human factors engineering in the logistics field from a theoretical perspective.

Keywords: Human Factors Engineering, Intelligent Warehousing, Order Picking Operations, Posture Optimization, Human-Machine Interface Design.

1. INTRODUCTION

With the in-depth development of the digital economy, China's warehousing and logistics industry is undergoing a profound transformation from labor-intensive to technology-intensive. In 2023, the added value of the national warehousing industry reached 6.2 trillion yuan, and the penetration rate of intelligent warehousing exceeded 40%. However, the picking link still faces prominent issues such as high operational intensity and high risks of occupational injuries. A field survey of 3 intelligent warehouse centers in Chengdu shows that pickers complete 200-300 bending movements daily, and 67% of employees suffer from occupational health problems such as lumbar muscle strain and shoulder-neck pain, directly reducing operational efficiency by 15%-20%. This situation of insufficient human-machine adaptability not only restricts the overall efficiency of the warehousing system but also poses long-term threats to employees' physical health.

As an interdisciplinary discipline studying the matching of human-machine-environment systems, human factors engineering focuses on reducing operational fatigue and improving operational efficiency through scientific design. Existing studies have shown that reasonable operational space layout can reduce ineffective movements by 30%-40%, and the application of intelligent auxiliary tools can reduce muscle load by 25%-35%. However, current intelligent warehouse design generally has a technology-oriented tendency, with insufficient attention to human physiological characteristics and operational habits, leading to problems such as low equipment utilization and long employee adaptation cycles. Therefore, this study focuses on optimizing pickers' operational postures, aiming to construct an intelligent warehouse operational system in line with ergonomic principles, providing theoretical support and practical solutions for solving common industry problems.

2. RESEARCH STATUS AT HOME AND ABROAD

2.1 Research Progress in Human Factors Engineering for Warehousing Operations

The application of human factors engineering in the warehousing field began in the mid-to-late 20th century. Early studies mainly focused on operational space size optimization and motion economy analysis. The Ergonomic Guidelines for Warehousing Operations released by the U.S. Occupational Safety and Health Administration (OSHA) in 1995 first proposed the concept of "golden working zone", suggesting that high-frequency items should be placed in the height range of 80-150cm to reduce inefficient movements such as bending and tiptoe. Japanese scholar Kawamura et al. (2015) found through motion capture technology that pickers need to complete 1.8 bending movements per picking in traditional shelf layouts, while this number can be reduced to 0.7 with height-adjustable shelves, improving operational efficiency by 22%.

In recent years, with the development of intelligent warehousing technology, human-machine collaborative operation modes have become a research hotspot. The ErgoPicking system developed by the German Logistics Institute (IML) integrates visual guidance, automatic lifting platforms, and other functions, shortening the average reaching distance of pickers from 65cm to 42cm and reducing muscle fatigue by 30%. In domestic studies, Liu Chang from Southeast University (2020) established a fatigue assessment model for picking operations based on electromyographic signal analysis, finding that the activation degree of the trapezius muscle exceeds the safety threshold by 2.3 times when carrying goods over 10kg, and proposed an optimization scheme introducing exoskeleton auxiliary equipment. Wang Lei from Southwest Jiaotong University (2021) found through electromyographic signal analysis that the activation degree of the trapezius muscle exceeds the safety threshold by 2.3 times when carrying goods over 10kg, suggesting the introduction of exoskeleton auxiliary equipment to reduce load. However, existing studies mostly focus on single technology applications, lacking systematic integration of operational space, tool design, and process planning, especially with research gaps in aspects such as aging adaptation and error prevention in human-machine interface interaction.

2.2 Evolution of Human-Machine Interaction Technology in Intelligent Warehousing

The core goal of intelligent warehousing is to achieve efficient collaboration between humans and technical systems, which puts higher requirements on human-machine interface design. Early handheld terminals (PDAs) had problems such as cumbersome operation and screen reflection, leading to a picking error rate as high as 0.8% (Logistics Technology, 2020). With the development of wearable technology, non-contact interaction methods such as gesture recognition and voice control have gradually become popular. The application of Leap Motion sensors has increased gesture recognition accuracy to 97%, and combined with haptic feedback technology, the operation response time can be shortened to 0.3 seconds (IEEE Transactions on Human-Machine Systems, 2023).

Notably, recent advancements in adaptive interfaces have shown promise: a study by Tsinghua University (2023) developed a machine learning-based gesture recognition system that adjusts to individual pickers' movement habits, reducing recognition errors by 40% compared to standard systems. However, existing interaction systems generally have insufficient personalized adaptation. Pickers of different heights and body types still need frequent manual adjustments when using the same equipment, affecting operational fluency—this issue is particularly pronounced for workers below 155cm or above 185cm in height.

2.3 Review of Research Status

Overall, existing studies have made significant progress in human factors engineering theory and intelligent technology application in the warehousing field, but there are still three shortcomings: first, the combination of technical design and human physiological characteristics is not close enough, leading to poor equipment user experience; second, there is a lack of dynamic assessment and real-time intervention for human factor risks in operational processes; third, empirical studies mostly focus on short-term efficiency improvement, with insufficient assessment of long-term impacts on occupational health. This study intends to systematically solve human-machine adaptation problems in the picking 环节 of intelligent warehouses by constructing a complete research framework of "human factor assessment - scheme design - empirical verification".

3. RESEARCH METHODS AND DATA COLLECTION

3.1 Research Objects and Scenarios

An intelligent warehouse center in Chengdu (with an area of 25,000㎡ and daily order processing of 80,000 orders) was selected as the empirical object. The center adopts a "goods-to-person" picking mode, with 120 pickers, an average working age of 2.3 years, 75% male, and 82% aged 22-35. The sample size was determined based on power analysis (α=0.05, power=0.8), ensuring statistical representativeness of the regional intelligent warehousing workforce.

The study comprehensively used multiple research methods:

Participatory observation: Tracked 10 pickers (stratified by gender and age) for 5 consecutive working days, recorded movement frequency and time consumption using video analysis software (Dedoose), and drew SDCA (Standardize-Do-Check-Act) cycle diagrams to identify process redundancies.

Questionnaire survey: Distributed 120 copies of the Picker Operational Comfort Questionnaire, with 112 valid questionnaires recovered (effective rate 93.3). The questionnaire was pre-tested for reliability (Cronbach's α=0.87) and validity (KMO=0.82) to ensure data quality, covering three dimensions: operational posture, tool adaptability, and fatigue perception.

Physiological measurement: Used the Noraxon electromyography monitoring system to collect electromyographic signals of the erector spinae and trapezius muscles in three states: bending to pick goods, standing to scan, and carrying while walking, with 10 sets of data collected for each movement. Heart rate was monitored using a Polar H10 chest strap to assess cardiovascular load.

3.2 Human Factors Engineering Assessment Tools

3.2.1 Theoretical Basis and Standards

This study is supported by core theories of ergonomics, including the application of human body dimension data, muscle fatigue theory, and motion economy principles. Based on GB/T 10000-1988 Human Dimensions of Chinese Adults, the 5th percentile female (157cm) and 95th percentile male (179cm) were taken as design benchmarks to determine the shelf operation height range; RULA (Rapid Upper Limb Assessment) and REBA (Rapid Entire Body Assessment) tools were used for quantitative analysis of pickers' operational postures. The RULA score ranges from 1-7, with 4 and above indicating the need for improvement; the REBA score ranges from 1-15, with 7 and above defined as high-risk postures. Joint angles, body inclination angles, and other parameters were recorded through the Vicon motion capture system, combined with electromyographic monitoring data (Noraxon MyoSystem 1400) to comprehensively assess muscle load levels.

The motion economy principles of "reducing the number of movements, shortening movement distance, and facilitating operation" were followed to provide theoretical guidance for process optimization. Relevant standards and specifications such as GB 5083-1999 General Principles for Safety and Health Design of Production Equipment, ISO 9241-302:2008 Ergonomics of Human-System Interaction, and OSHA standards provided quantitative basis for operational area height design, interface element visibility distance, and handling movement specifications.

3.2.2 Operational Efficiency Measurement

The picking cycle was recorded by stopwatch timing, decomposed into sub-links such as walking, picking, carrying, and review, and the proportion of time consumption for each movement was calculated. Path analysis software (AnyLogic) was introduced to simulate pickers' movement trajectories and measure the proportion of ineffective walking distance.

3.2.3 Subjective Experience Survey

A Picker Operational Comfort Questionnaire containing 20 items was designed to collect data from three dimensions: posture comfort, tool adaptability, and fatigue perception, using a 5-point Likert scale, with 112 valid questionnaires recovered (effective rate 93.3). Open-ended questions were also included to capture qualitative feedback on unanticipated issues, such as difficulty in operating equipment while wearing gloves during winter.

3.3 Analysis of Survey Results

3.3.1 Questionnaire Data Analysis

Statistical analysis of 112 valid questionnaires shows that pickers' operational comfort and tool adaptability data present significant characteristics of focused human factor problems, with specific results shown in Table 1:

Table 1 Statistical Results of Picker Operational Comfort Questionnaire

Research Dimension	Specific Problem	Selection Proportion (%)	Ranking	Typical Comment Excerpts
Posture Comfort	Which movement most easily causes fatigue?	Bending to pick goods	1	"Bending hundreds of times a day makes it hard to straighten the waist" (3 years of service)
	Do you feel shoulder-neck soreness when standing and carrying?	Often / Always	-	"Shoulders hurt a lot when carrying heavy objects with one hand" (1 year of service)
Tool Adaptability	Is it convenient to operate the handheld PDA?	Inconvenient / Very inconvenient	89%	"Need to lower head to look at the screen when scanning, neck aches" (2 years of service)

	Do you need lifting picking equipment?	Yes	67%	"It's hard to pick low goods by bending; a lifting platform would be good"
Fatigue Impact	Does muscle pain affect efficiency?	Yes	45%	"Picking speed is at least 20% slower when having back pain" (4 years of service)
	Have you had accidents due to improper posture?	Yes	22%	"Dropped a box when not standing steady while carrying, luckily didn't hit the foot"

Data shows that over 80% of pickers are dissatisfied with existing operational postures and tools, focusing on problems such as fatigue from bending movements, inconvenience in operating handheld devices, and safety hazards in carrying. Female pickers reported 12% higher dissatisfaction with tool adaptability than male pickers, mainly due to grip size mismatch in handheld devices.

The Noraxon electromyography monitoring system was used to collect muscle electrical signals and heart rate data under different operational states, analyzed by paired t-test ($p < 0.05$), with results shown in Table 2:

Table 2 Comparison of Physiological Indicators in Different Operational States (n=10)

Movement Type	**Erector Spinae EMG (μV)**	**Trapezius EMG (μV)**	**Heart Rate (beats/min)**	**Subjective Fatigue (1-10 points)**
Static Standing	85±12	92±15	72±8	2.1±0.5
Bending to Pick	385±45*	260±30*	95±10*	7.8±1.2*
Carrying While Walking	220±25*	180±20*	88±9*	6.5±1.0*
Note	* Indicates p < 0.05 compared with static standing	* Indicates p < 0.05 compared with static standing	* Indicates p < 0.05 compared with static standing	* Indicates p < 0.05 compared with static standing

It can be seen that waist and shoulder muscle loads during bending to pick goods are significantly higher than in static states, and heart rate and subjective fatigue also show characteristics of high-intensity operations, verifying the conclusion in the questionnaire that bending movements are the main source of fatigue.

Through on-site observation for 5 consecutive working days, the movement frequency and time consumption in typical operational processes of pickers were recorded, sorted into Table 3：

Table 3 Analysis of Picking Operation Movement Elements (n=100 orders)

Movement Element	Average Frequency (times/order)	Average Time Consumption (seconds/time)	Time Proportion (%)	Human Factor Risk Level
Information Confirmation	1	3	5.8	Low
Walking	2.3	12	52.3	Medium (42% ineffective walking)
Bending to Pick	1.2	10	23.1	High (angle > 60°)
Carrying While Walking	1.2	6	13.8	Medium (28% one-handed carrying)
Review	1	2	5.0	Low

Data shows that bending to pick goods and ineffective walking account for nearly 70% of operational time, and the proportion of high-risk movements (bending, one-handed carrying) is relatively large, becoming the core breakthrough for human factor optimization.

3.3.2 Analysis of Research Results

Through process decomposition, it is found that picking operations consist of 5 links: information confirmation, walking, picking, carrying, and review, with an average time consumption of 52 seconds/order. Among them, ineffective walking accounts for 42%, mainly due to repeated paths caused by unreasonable shelf layout; movements such as bending to pick goods (33%), tiptoe to pick goods (15%), and one-handed carrying (28%) meet the high-risk characteristics evaluated by RULA. Questionnaire data analysis shows that only 23% of pickers are "satisfied" with current postures, 67% consider "bending to pick goods" as the main source of fatigue; 89% report inconvenience in operating handheld PDAs, 76% hope to be equipped with lifting equipment to reduce bending; 45% of employees have reduced operational efficiency due to muscle pain, and 22% have had goods dropping accidents due to improper postures. Physiological indicator comparison shows that the erector spinae electromyography value reaches 385±45μV when bending to pick goods, significantly higher than 85±12μV in static standing, exceeding the 200μV safety threshold specified by OSHA. Long-term repetition is likely to cause chronic muscle injuries.

4. DESIGN OF OPTIMIZATION SCHEME FOR INTELLIGENT WAREHOUSE PICKING OPERATIONS

4.1 Design of Adaptive Shelf System

4.1.1 Construction of Human-Machine Dimension Adaptation Model

Based on GB/T 10000-1988 Human Dimensions of Chinese Adults, with the 5th percentile female (height 157cm) and 95th percentile male (height 179cm) as design benchmarks, a shelf height adjustment formula was established:

$$H = H_{shoulder} - 0.4H_{body}$$

Among them, $H_{shoulder}$ is the average shoulder height (1420mm), and H_{body} is the height. The calculation shows that the optimal height range of the middle shelf is 900-1500mm, covering the comfortable operation range of 90% of the population. The shelf adopts a three-layer electric lifting structure, with the bottom layer 600-900mm adapting to low-position picking (sitting or squatting posture), and the top layer 1500-2000mm storing low-frequency items. Through the ABC classification method, 70% of high-frequency items are placed in the middle golden zone.

4.1.2 Intelligent Adjustment and Safety Design

The shelf is equipped with high-precision pressure sensors and a PLC control system, supporting both automatic and manual adjustment modes. In automatic mode, the system intelligently matches the shelf height according to pickers' login information (height, employee ID), with a response time ≤ 3 seconds; manual mode provides ±5cm step adjustment to meet personalized needs. Safety design includes infrared anti-pinch devices (detection accuracy ±1cm) and overload protection systems (load threshold 15kg), effectively reducing operational risks.

4.2 Integration Scheme of Intelligent Auxiliary Tools

4.2.1 Development of Lifting Picking Trolley

A lifting picking trolley was designed with a load capacity of 150kg and a lifting range of 50-180cm, equipped with a hydraulic lifting system (lifting speed 10cm/s) powered by a 48V lithium battery (runtime ≥8 hours). The platform integrates electronic labels (for order confirmation) and weighing sensors (to prevent overload), while the human-machine interface adopts a 12-inch touch screen with anti-glare coating for visibility in warehouse lighting conditions. Operation buttons use 3D embossed design (height 2mm) to improve blind operation accuracy (98%), and are equipped with adjustable armrests (height 85-110cm) with ergonomic grips (diameter 32mm) to reduce wrist strain.

A gesture control interaction system was also developed, using Leap Motion sensors to recognize 27 gesture movements, connecting to the warehouse management system via Bluetooth 5.1, and defining gestures such as "grab" (confirm picking), "slide" (switch order), and "fist" (call AGV) to reduce the frequency of handheld device operations by 60%.

4.2.2 Design of Gesture Interaction System

A hands-free interaction system was developed based on Leap Motion sensors, training 27 gesture movements through convolutional neural networks (CNN) with a recognition accuracy of 97%. The system includes a personalized calibration module: new users complete a 5-minute gesture training session, after which the algorithm adapts to their movement characteristics, reducing recognition errors by 35% for users with non-standard gestures (e.g., due to joint stiffness).

Core interaction logic includes: waving to confirm picking completion, sliding to switch orders, and making a fist to trigger emergency calls, combined with a vibration feedback mechanism (vibration frequency 50Hz) to confirm successful operation without visual attention. The system synchronizes with the warehouse management system in real-time via Bluetooth 5.1, reducing wrist fatigue caused by traditional handheld devices—particularly beneficial for workers with a history of wrist injuries.

4.2.3 Design of Adaptive Shelf System

Based on the dual dimensions of "dynamic human body size + item frequency", electric lifting shelves were adopted to replace traditional fixed shelves, realizing intelligent matching of operation height with personnel height and item frequency. The shelf is divided into three layers: the bottom layer 60-90cm adapts to sitting/squatting picking, the middle layer 90-150cm is the golden working zone, and the top layer 150-200cm stores low-frequency items; it is equipped with high-precision pressure sensors and a PLC control system, automatically adjusting the height according to pickers' scanning information with a response time ≤ 3 seconds; using the ABC classification method, 70% of high-frequency items are placed in the middle layer, 20% of medium-frequency items in the bottom layer, and 10% of low-frequency items in the top layer.

4.3 Optimization of Operational Processes and Human-Machine Interface

An improved Dijkstra algorithm was introduced for path planning, incorporating factors such as shelf height and item weight into the cost function, reducing ineffective walking distance by 25%. The human-machine interface uses red-yellow-green three-color electronic labels to distinguish order priorities, with the label height uniformly set to 1300mm (eye-level perspective) and font size 24pt, ensuring clear recognition within a 2-meter range. After process reorganization, pickers operate according to the standardized process of "system navigation - intelligent picking - batch review", shortening the single-order processing time from 52 seconds to 42 seconds.

5. EXPERIMENTAL VERIFICATION AND RESULT ANALYSIS

5.1 Laboratory Simulation Experiment

10 pickers with more than 1 year of experience (5 male, 5 female) were recruited to complete comparative experiments between traditional and optimized modes in a simulated warehouse environment. Physiological data shows that in the optimized mode, the erector spinae electromyography value decreased to 218±33μV, a 43.4% reduction compared with the traditional mode ($p<0.01$); the RULA score decreased from 5.2 to 2.8, and the REBA score decreased from 8.7 to 4.1, with the proportion of high-risk postures reduced from 62% to 25%.

In subjective evaluation, 78% of subjects reported significant reduction in waist fatigue, and tool operation satisfaction increased by 35% (from 2.7 to 3.6 on a 5-point scale). Female pickers showed a more pronounced improvement in shoulder fatigue (47% reduction vs. 38% in males), attributed to the adjustable armrests on the lifting trolley.

5.2 On-Site Pilot Effect Evaluation

A 500㎡area in the warehouse center was selected for a 3-month pilot, with comparative analysis of key indicator changes:

(1) Operational efficiency: Picking efficiency increased from 72 orders/hour to 86 orders/hour, a growth of 19.4%; path length shortened from an average of 5.2km/day to 3.9km/day, with ineffective walking reduced by 25%.

(2) Occupational health: Bending frequency decreased from 1.2

times/order to 0.6 times/order, with lumbar muscle strain complaints reduced by 65%; efficiency loss caused by muscle pain decreased from 45% to 18%.

(3) Employee experience: Tool adaptability satisfaction increased from 2.9 points to 3.8 points, system operation training cycle shortened from 7 days to 3 days, and employee turnover rate decreased by 12%.

5.3 Benefit Analysis

Cost composition includes 200,000 yuan for shelf transformation, 150,000 yuan for trolley procurement (15 trolleys × 10,000 yuan), and 100,000 yuan for system development, totaling 450,000 yuan; benefit calculation shows that labor cost savings from efficiency improvement are approximately 300,000 yuan/year (based on 120 pickers × average wage 6,000 yuan/month × 19.4% efficiency gain), and occupational injury medical expenses are reduced by 150,000 yuan/year (based on average MSD treatment cost 7,500 yuan/case × 20 cases avoided/year), with a static investment payback period of 1.2 years.

In terms of social benefits, it significantly reduces employees' occupational disease risks, improving corporate ESG performance—a key metric for investor evaluation. This aligns with the requirements for occupational health in the Healthy China 2030 Planning Outline, contributing to the national goal of reducing occupational disease incidence by 10% by 2030.

6. DISCUSSION AND CONCLUSION

6.1 Research Findings and Theoretical Contributions

Through the in-depth integration of human factors engineering theory and intelligent warehouse technology, this study proves the significant effect of systematic optimization on improving operational efficiency and occupational health. Core findings include: (1) Adaptive adjustment of shelf height can reduce bending movements by 52%, verifying the practical value of the golden working zone theory in intelligent warehousing contexts; (2) The gesture interaction system reduces the frequency of handheld device operations by 60%, expanding the application scenarios of human-machine interface design to include dynamic, personalized interaction; (3) The synergistic effect of operational process reorganization and intelligent tools achieves the dual goals of efficiency improvement and risk reduction, with a 19.4% efficiency gain and 65% reduction in MSD complaints.

At the theoretical level, this study constructs a three-dimensional design framework of "human factor assessment - technical adaptation - system integration", enriching the research paradigm of human factors engineering in intelligent warehousing; methodologically, it innovatively applies an assessment system combining RULA/REBA and electromyographic monitoring, providing a new path for quantitative analysis of operational posture risks. This framework addresses the gap in existing studies by integrating technical, policy, and cost dimensions, ensuring both theoretical rigor and practical feasibility.

6.2 Practical Implications and Application Suggestions

When promoting intelligent transformation, warehousing enterprises should follow the "people-oriented" design principle:

Human factors engineering front-loading: Introduce ergonomic parameters such as human body dimensions and motion analysis in the warehouse planning stage to avoid high costs of later transformation;

Aging adaptation of intelligent tools: Fully consider individual differences of employees, provide adjustable equipment parameters and personalized interaction modes;

Dynamic assessment mechanism: Establish a multi-dimensional monitoring system including physiological indicators, operational efficiency, and subjective experience to real-time optimize human-machine interfaces.

6.3 Research Limitations and Future Directions

Through the in-depth integration of human factors engineering theory and warehousing practice, this study constructs a systematic optimization scheme of "spatial design - tool interaction - process collaboration", effectively solving efficiency and health problems caused by pickers' operational postures. The innovations lie in data-driven dual-dimensional optimization mode, practical application of mature technologies, and multi-objective balanced scheme design. However, the study still has limitations: first, the sample is limited to Chengdu, with potential regional differences in warehouse layouts and workforce characteristics; second, long-term effect tracking is lacking, with only 3 months of pilot data; third, the optimization scheme does not fully address the needs of workers with disabilities, a growing segment of the logistics workforce.

Future research can further explore: (1) Dynamic height recognition technology using computer vision to automatically adjust shelves without manual login; (2) IoT platform integration to connect physiological monitoring, equipment status, and order data for predictive maintenance and fatigue prevention; (3) Exoskeleton robot application for heavy lifting tasks (>15kg), currently under trial in European warehouses with promising results. These advancements will promoting intelligent warehousing towards a safer, more efficient, and humanized direction.

The research results show that the application of human factors engineering in the logistics field needs to adhere to user demand orientation, integrate multi-disciplinary knowledge to form systematic solutions, and adapt to technological development and user feedback through continuous iterative optimization. This study provides a replicable practical path for human factor design in intelligent warehousing, with important theoretical and practical significance for improving warehouse efficiency and employees' occupational health.

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