GAS Journal of Engineering and Technology (GASJET)
Volume 3 | Issue 7, 2026 Homepage: https://gaspublishers.com/gasjet-home/ ISSN: 3048-5800

Research on the Analysis and Improvement of Procedures for Collecting Items from Smart Delivery Cabinets

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Received: *20.06.2026* | ***Accepted:*** *17.07.2026* | ***Published:*** *18.07.2026*

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DOI: *10.5281/zenodo.21427889*

Abstract **Original Research Article**

Smart parcel lockers serve as core infrastructure for urban last-mile logistics distribution, yet existing designs predominantly prioritize spatial efficiency while neglecting pickup comfort and cognitive ease of use. This study examines community-operated Fengchao standard lockers, employing the NIOSH lifting equation and Fitts' law to conduct human factors analysis from biomechanical and cognitive load perspectives. Results indicate that the top compartment exceeds the reach range defined by the 5th percentile for female users; the lifting index for 10 kg packages at the bottom compartment reaches 1.12, surpassing the safety threshold; touchscreen operation presents significant difficulty, and glare exacerbates cognitive load. Based on these findings, this paper proposes optimization strategies across four dimensions to inform more user-friendly design and operational practices for parcel lockers.

Keywords: Smart parcel lockers, Ergonomics, Biomechanics, Cognitive load, Human-computer interaction.

I. Introduction

With the rapid development of e-commerce and last-mile logistics, smart parcel lockers have become standard facilities in communities and office buildings, effectively addressing the mismatch between delivery timelines and users' schedules[1]. The stay-at-home lifestyle during the COVID-19 pandemic significantly boosted demand for online shopping and home delivery services, driving continuous innovation in last-mile logistics solutions[2]. Current locker designs primarily prioritize operational efficiency by maximizing compartment capacity while minimizing space occupation, often neglecting key user factors such as physical dimensions, operational postures, and cognitive processing patterns. In practice, users of varying heights frequently encounter challenges including difficulty accessing top compartments, excessive bending required to retrieve items from lower compartments, and touchscreen glare impairing usability in outdoor environments. These issues not only directly impact user experience but also pose potential health risks, particularly due to chronic musculoskeletal strain in the shoulders, neck, and lumbar region caused by frequent improper usage postures.

Current research on parcel lockers primarily focuses on layout planning and operational models, with most studies employing software simulations as the main methodology, lacking quantitative analysis based on field measurement data. Additionally, most studies concentrate solely on spatial dimension compatibility while rarely addressing both biomechanical stress and cognitive interaction demands, indicating a need for enhanced systematicity. This paper takes Fengchao standard lockers in community settings as the primary research subject, collects key locker parameters through field measurements, conducts quantitative evaluations using classical ergonomics tools, systematically identifies human factor issues throughout the retrieval process, and proposes actionable improvement strategies. The findings align with professional standards in logistics engineering and management while providing valuable insights for user-friendly design of similar facilities.

II. Research and Methods

(1) Literature Review and Theoretical Tools

The smart parcel locker represents the core intelligent solution for the "last mile" scenario in end-point logistics, offering exceptional security and privacy benefits throughout the sending and receiving process[3].

Current domestic research on smart parcel lockers primarily falls into two major categories. The operational management approach focuses on quantitative modeling of delivery model selection and multi-scenario pricing, with research emphasis on optimizing corporate efficiency [4]. The human-machine interaction design approach relies mainly on simulation software for virtual analysis to identify compatibility issues in device dimensions and layout, yet generally lacks empirical data from real-world scenarios [5]. While age-friendly interaction design has established a systematic evaluation and optimization framework in e-commerce, targeted research specifically for community-based smart locker applications remains significantly lacking [6].

At the theoretical tool level, three classical methods provide a solid foundation for this study. The NIOSH Manual Lifting Equation is a universal tool for biomechanical risk assessment, capable of quantitatively identifying musculoskeletal injury risks associated with lifting tasks based on core operational parameters7. This equation has undergone localization validation for the China population, and after adjusting relevant parameters, its assessment results better align with the physical characteristics of manual labor in domestic populations8. Fitts' Law elucidates the trade-off between speed and accuracy in goal-directed movements9 and can quantify operational loads through difficulty indices10.

Given the limitations of existing research, this paper establishes a multidimensional quantitative evaluation system: it employs the GB/T 10000-2023 national standard to assess hardware dimensional compatibility[11], utilizes the NIOSH manual lifting equation for biomechanical risk assessment, and applies Fitts' law to quantify interface interaction difficulty.

(II) Field Research Plan

The study focused on the Fengchao standard parcel lockers at the entrance of a residential community. These lockers consist of one main unit and four auxiliary units, totaling 84 compartments, making them representative samples. Three datasets were collected to analyze locker parameters, user behavior, and operational postures.

The first group measured the cabinet dimensions: total height 210 cm, width 450 cm, depth 50 cm. Grid openings are positioned at heights of 181 cm from the bottom edge of the top layer, 120–160 cm for the middle layer, 30 cm and 60 cm respectively for the bottom layer; each opening has a depth of 45 cm. The touch screen center is located at 140 cm, with the primary buttons measuring approximately 2.5 cm in size.

The second group observed user behavior. During peak hours, observations were conducted over two hours, recording data from 32 users. Key metrics included total pickup time, number of touch screen errors, proportion of users requiring toe-pushing or significant bending, and frequency of posture adjustments due to reflections.

The third group of sampling operation postures involved adult females with a height of 173 cm (exceeding the 95th percentile for women) as subjects, who were tested performing standing operations on touchscreens and retrieving items from both the top and bottom layers, for subsequent load analysis.

Parameter Category	Measurement Items	measured value	unit
Total Size	Total height of the cabinet	210	cm
	Total width of the cabinet	450	cm
	Front-to-back depth of the cabinet	50	cm
Grid Height	Height of the bottom edge of the top grid cell from the ground	181	cm
	Middle-layer grid cell height range	120 – 160	cm
	Height of the lower edge of the second sub-grid cell	60	cm
	Height of the bottom edge of the lowest grid cell	30	cm
	Internal depth of the grid cell	45	cm
Interaction Interface	Touchscreen center height above ground	140	cm
	Minimum width of core operation buttons	2.5	cm

Table 2-1 Main Dimensional Parameters of Fengchao Standard Delivery Lockers

(III) Setting of Quantitative Calculation Parameters

The general expression of the NIOSH lifting equation states that the recommended weight limit equals the product of the load constant and various correction factors, as given by the formula:

□□□ = □□ × □□ × □□ × □□ × □□ × □□ × □□

Among □□□□□□□□□□□□□□these, is the load constant, with a value of 23 kg; is the horizontal distance coefficient, reflecting the impact of the horizontal distance between the hand and the trunk on lifting capability; is the vertical height coefficient, reflecting the influence of the starting height during lifting; is the vertical displacement coefficient, reflecting the effect of the vertical lifting distance; is the asymmetry coefficient, reflecting the impact of trunk torsion angle; is the frequency coefficient, reflecting the influence of lifting frequency; and is the coupling coefficient, reflecting the ease of gripping the package.

Parameter Name	symbol	short-cut process	Setting Basis
Load Constant	LC	23 kg	NIOSH Standard Reference Value
horizon range	H	45 cm	Internal depth of the grid opening; horizontal distance for manual item retrieval
Starting Vertical Height	V	30 / 60 cm	Minimum/Second-lowest grid slot packaging placement height
vertical displacement	D	70 cm	The conventional displacement of the package from its slot position to a height equivalent to the waist-to-abdominal region.

Parameter Name	symbol	short-cut process	Setting Basis
Asymmetric Angle	A	0°	The user is retrieving items from the cabinet without any torsion of the trunk.
Retrieval Frequency	F	Single Low Frequency	Low-frequency characteristic for daily collection; frequency coefficient set to 1.0
Coupling Level	C	same as	Standard express packages do not have dedicated handles; the coupling coefficient is set to 0.95.

Table 2-2: Values of parameters for the NIOSH proposed equation

Based on the actual retrieval scenarios at the bottom level, the parameter values are set as follows: The horizontal distance is 45 cm, corresponding to the internal depth of the compartment—the horizontal distance required for the user's hand to reach the bottom of the compartment when retrieving items; the vertical starting heights are 30 cm and 60 cm, corresponding to the package placement heights of the lowest and second-lowest compartments respectively; the vertical displacement is 70 cm, representing the standard movement needed to lift a package from the compartment to waist level; the asymmetric angle is 0 degrees, indicating the user faces directly toward the cabinet without torso rotation; the lifting frequency adopts a low-frequency mode, reflecting the typical low-frequency usage pattern of regular users, with a frequency coefficient of 1.0; the coupling level is moderate, reflecting that ordinary parcels lack dedicated handles and exhibit average grip stability, with a coupling coefficient of 0.95.

Fitts' law employs the widely used Shannon formula in human-computer interaction, expressed as:

$$ID = \log_2(\frac{D}{W} + 1)$$

The first $IDDW$ parameter is the difficulty index, measured in bits; the second is the operation distance—the distance from the hand to the target button; and the third is the button width. In this calculation, the operation distance is set at 45 cm, corresponding to the typical hand-eye distance when operating the touchscreen in an upright position; the button width is set at 2.5 cm based on field measurements, representing the minimum effective size of the primary operation button.

III. Analysis and Discussion

(1) Biomechanical Analysis of Jaw Height

1. Accessibility Analysis of the Top Grid Cells

Field measurements revealed that the bottom edge of the top compartment is 181 cm above ground, with an internal depth of 45 cm. Based on human anatomical standards, a subject standing 173 cm tall can only reach approximately 190 cm when raising their arms vertically – barely touching the compartment's lower edge. To access the interior and retrieve items, the arm must extend forward by 45 cm, significantly reducing effective reach height. The subject then needs to stand on tiptoe and fully extend their arm to touch the package's edge, requiring shoulder abduction angles approaching 90 degrees and sustained neck extension for visibility inside the compartment – a highly demanding posture. These findings demonstrate that even female users exceeding the 95th percentile height face near-limiting physical challenges when accessing packages from the top compartment.

For users with medium-to-low stature, who constitute the majority of female consumers, accessibility challenges are particularly pronounced. According to national standards, the 50th percentile height for adult women is approximately 160 cm, while the 5th percentile is around 149 cm. The optimal operating height in a standing position corresponds to shoulder height levels: about 135 cm for the 50th percentile and 128 cm for the 5th percentile. Using this comfort threshold as reference, the lower edge of the top compartment exceeds the comfortable operating height by approximately 46 cm for women at the 50th percentile and by 53 cm for those at the 5th percentile. Considering the additional height reduction caused by a 45 cm compartment depth, shorter women cannot complete retrieval tasks even on tiptoe, rendering the top compartment largely unusable for this demographic. Moreover, tiptoeing during retrieval destabilizes body balance; if the package carries significant weight, sudden center-of-gravity shifts during extraction may pose safety risks such as falls.

2. Assessment of lumbar spine load on the lower grid cells

The lower edge height of the bottom grid compartment ranges from 30 to 60 cm, requiring subjects to bend significantly forward with a trunk tilt angle of approximately 50–60 degrees when retrieving items. The act of inserting one hand into the compartment to grasp packages also imposes asymmetric torsional loads. To quantify lumbar spine risks under this posture, the NIOSH lifting equation was applied to calculate the recommended weight limits for both the lowest and second-lowest compartments.

For the lowest grid cell, determine the initial $V = 30\text{cm}$ vertical height of material pickup and calculate each value by substituting it into the respective correction coefficient formula:

$$Horizontal\ Distance\ Coefficient: HM = \frac{25}{H} = \frac{25}{45} \approx 0.556$$

$$Vertical\ Height\ Factor: VM = 1 - 0.003|V - 75| = 1 - 0.003 \times 45 = 0.865$$

$$Vertical\ displacement\ coefficient: DM = 0.82 + \frac{1.8}{D} = 0.82 + \frac{1.8}{70} \approx 0.846$$

The values of other parameters are $AM = 1.0 FM = 1.0 CM = 0.95 LC = 23\text{kg}$: asymmetry factor, frequency factor, coupling factor, and load constant. Substitute all parameters into the recommended weight limit formula:

$$RWL = 23 \times 0.556 \times 0.865 \times 0.846 \times 1.0 \times 1.0 \times 0.95 \approx 8.9\ kg$$

The recommended safety weight limit for the lowest-level grid cell retrieval operation is approximately 8.9 kilograms.

Using this limit value as the benchmark, the $LI = \frac{L}{RWL}$ index calculation formula is:

When the lifting index $L = 10\text{kg} LI \approx 1.12$ exceeds the safety threshold of 1.0 based on the actual weight of the package, it indicates a significant risk of lower back injury when lifting a 10-kilogram package in this posture.

For the sub-base grid cell at the specified $V = 60\text{cm}$ vertical height, similar calculations yield a recommended weight limit of approximately 9.8 kg; the lifting index for a 10 kg package is about 1.02, both values approaching the safety threshold.

In practical operational scenarios, current slot allocation solely relies on package dimensions to match slot sizes without considering weight factors, potentially assigning heavy items to lower slots. When users lift heavy objects while bending significantly – a scenario corresponding to the highest-risk condition in the NIOSH equation – prolonged exposure may lead to lumbar spine-related health issues. Moreover, the asymmetric force application caused by inserting one hand into the slot further increases torsional stress on the lumbar spine, resulting in actual risks exceeding the baseline values calculated by the equation.

3. Matching Analysis of Middle Grid Cells

The lower edge height of the middle-level compartment is consistently maintained between 120 and 160 cm, corresponding to the comfortable range for most adults when arms are extended naturally or slightly raised. For adult females, the 50th percentile elbow height is approximately 99 cm and shoulder height about 135 cm, with the core area of the compartment precisely falling within this optimal range. Users taller than 160 cm can maintain an essentially upright posture during item retrieval, with shoulder joints in a naturally relaxed or slightly elevated position, resulting in low biomechanical stress.

This zone represents the optimal collection area from a human factors perspective; however, due to constraints imposed by the overall cabinet height and tiered design, the number of compartments in the middle layer is limited and insufficient to accommodate all package storage requirements. During operation, a significant number of packages are forced to be placed in top or bottom compartments, creating a structural imbalance where the central area experiences supply shortages while the end areas suffer from low utilization rates—this constitutes the fundamental root cause of current human factors issues in parcel lockers.

Grid Level	altitude band (From the ground)	Typical operating posture	Biomechanical load levels
High Area	160 – 210 cm	Elevate the arms, stand on tiptoes, and tilt the neck backward	High shoulder load Poor center of gravity stability
Medial region	90 – 160 cm	The trunk is upright, with the arms raised naturally.	The lumbar spine bears the lowest load. Most comfortable operation
Low Area	30 – 90 cm	The trunk is significantly tilted forward and bent over.	The shear force on the lumbar spine is significant. High risk of injury

Table 3-1 Comparison of human characteristics at different grid heights

(II) Analysis of Cognitive Load in Touchscreen Interaction

The touchscreen serves as the primary interface for user interaction with parcel lockers, and its design rationality directly impacts operational efficiency and cognitive load. Field measurements indicate that the touchscreen's center is approximately $ID = \log_2\left(\frac{D}{W} + 1\right)$ 140 *cm above ground, while the minimum size of core operation buttons is about* 2.5 *cm. Applying Fitts' law yields the corresponding operational difficulty of these buttons, calculated by the formula:*

Substitute the $D = 45\text{cm}W = 2.5\text{cm}$operation distance and button width to obtain:

$$ID = \log_2(\frac{45}{2.5} + 1) = \log_2 19 \approx 4.25bit$$

The current button operation is moderately challenging, and in outdoor settings, this difficulty is further exacerbated by environmental factors.

Reflection issues caused by outdoor lighting are the most prominent factor affecting user interaction experience. Touchscreens in parcel lockers typically use mirror-like glass, which produces intense reflections under direct sunlight. For users standing at 173 cm height, their line of sight is roughly aligned with the screen center, making reflection interference relatively manageable; however, reflections in the button areas can still cause operational delays. For users under 160 cm height, whose line of sight is below the screen center and forms a larger angle with the screen's normal surface, ambient light reflections enter their field of view directly, significantly exacerbating reflection interference. Behavior observation data shows that among 32 users, 11 adjusted their posture repeatedly due to reflections (over 30%); eight experienced incorrect code entry during retrieval, most of which was accompanied by recognition difficulties caused by reflections.

Observation Project	Number of visits	proportion
The retrieval process requires standing on tiptoes.	9	28.1%
The retrieval process requires significant bending forward.	14	43.8%
The body posture was repeatedly adjusted due to reflection issues.	11	34.4%
Error occurred when entering the pickup code	8	25.0%

Table 3-2 Statistical Results of User Collection Behavior Observation (n=32)

Figure 3-1: Reflections on the operation screen interfere with visibility.

The cognitive burden associated with the retrieval process itself cannot be overlooked. Retrieval codes typically consist of 6 to 8 digits, approaching the capacity limit of human working memory. While users can usually input them quickly under normal circumstances, when visual processing causes reduced information clarity, they must allocate additional cognitive resources to recognize screen content—this not only prolongs operation time but also increases the likelihood of input errors. Elderly users face particularly significant challenges in this context due to declining vision and slower cognitive processing speeds, often requiring multiple attempts to complete the task[12].

The screen height and button size design also fail to adequately account for variations in user body types. While a 140 cm screen center height is suitable for taller users, it creates significant challenges for shorter individuals: poor viewing angles require constant arm elevation during operation, leading to shoulder fatigue over prolonged use. Additionally, smaller buttons have reduced error tolerance in outdoor environments; even slight hand movement while walking significantly increases the risk of accidental touches, further compromising operational smoothness.

After optimization, the button width has been increased to 3.5 cm. Using the formula for calculation:

$$ID = \log_2(\frac{45}{3.5} + 1) = \log_2 13.86 \approx 3.79bit$$

The operation difficulty has been reduced by approximately 11% compared to before optimization, effectively shortening processing time and lowering the misactivation rate.

(III) Summary of Key Human Factors Issues

Through analysis combining biomechanics and cognitive interaction dimensions, the core human factors issues of current parcel lockers can be summarized into three levels. The first level involves the vertical layout of compartments not matching the physical dimensions of Chinese adults: the top compartment height exceeds the effective reach range of most female users, while the bottom compartment requires all users to bend significantly during operation. Only the middle compartment exhibits favorable human factors characteristics but suffers from insufficient capacity, resulting in a structural issue where both ends have poor usability while the central area faces resource constraints.

The second issue lies in the fact that the slot allocation logic does not account for biomechanical costs. The current algorithm relies solely on packaging dimensions as the sole matching criterion, completely ignoring weight factors and variations in load distribution across different handling postures; heavy items may be randomly assigned to either top or bottom slots, significantly increasing health risks during operation. This issue falls within operational management parameters and can be optimized without hardware modifications, yet it has not received adequate attention.

The third issue lies in the interaction interface design's lack of adaptation to outdoor usage scenarios. Problems such as screen glare from reflective surfaces, small button sizes, and limited viewing angles collectively increase cognitive load during operation, particularly posing significant accessibility challenges for short-statured users and elderly individuals, highlighting notable shortcomings in user-friendliness.

The common root cause of these three types of issues lies in the fact that current delivery lockers are designed and operated primarily with storage efficiency and operational costs as core considerations, failing to incorporate human size variations, biomechanical load limits, and cognitive processing characteristics of different user groups into initial design inputs. This fundamentally reflects a lack of application of ergonomics principles in end-point logistics facilities.

IV. Improvement Plan

(1) Optimization Plan for Vertical Division of Grid Cells

To address the structural issues of the grid layout, the cabinet body can be vertically divided into three functional zones based on anthropometric data, with each zone serving distinct storage purposes, thereby enhancing overall ergonomics without altering the total height of the cabinet. The height of each zone is determined according to China's adult anthropometric data, ensuring compatibility with the operational capabilities of the majority of users.

The low zone is designated at a height of 30 to 90 cm above the ground, requiring users to bend forward for retrieval and imposing significant biomechanical strain; therefore, it is suitable only for storing lightweight and compact packages to avoid physical strain during bending. The middle zone spans 90 to 160 cm above ground, covering a comfortable reach range from the femoral fifth percentile elbow height for females to the male shoulder height at the 95th percentile, allowing the trunk to remain upright during retrieval with minimal lumbar load, making it the preferred area for heavy packages. The high zone ranges from 160 to 210 cm above ground, where retrieval requires raising arms or even standing on tiptoes, and is intended solely for extremely light items to minimize safety risks associated with reaching such heights.

The zoning functionality is indicated by color-coded labels on cabinet surfaces, enabling users to quickly grasp intended configurations. For new cabinets, the slot heights at the top and bottom levels can be appropriately reduced while increasing the proportion of slots in the central zone, optimizing resource allocation at the hardware level. For existing cabinets, backend algorithms can adjust slot allocation priorities to achieve seamless implementation of functional zoning.

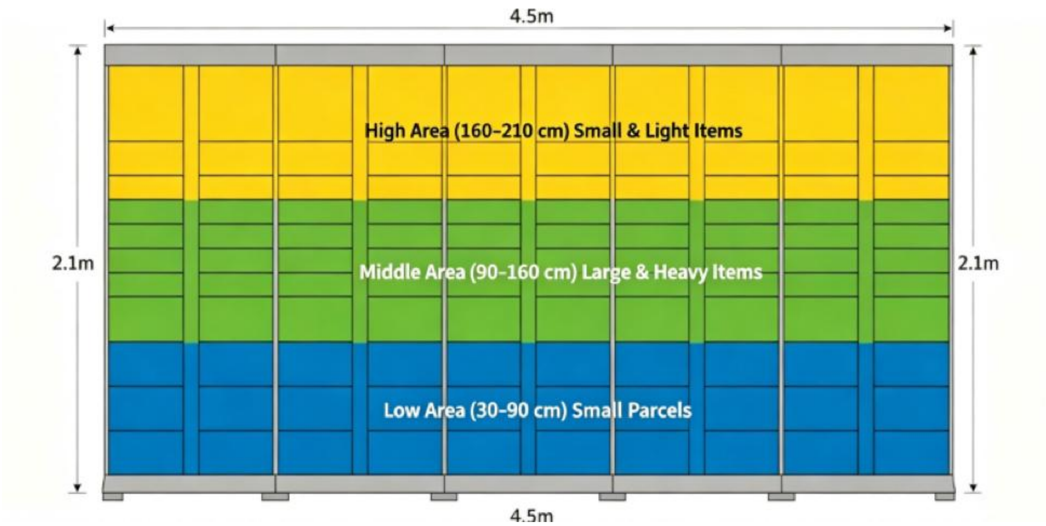

Figure 4-1: Design diagram for grid optimization distribution

(II) Upgrade of the Weight Matching Allocation Algorithm

Without altering the cabinet hardware, optimizing the compartment allocation algorithm represents the most cost-effective improvement measure. It is recommended to introduce a parcel weight parameter alongside existing size-matching criteria and establish a correlation rule between weight and compartment positioning, thereby reducing users' biomechanical risks at the operational level.

The specific matching rules can be configured across three tiers. Packages weighing over 3 kg are prioritized for placement in the middle compartment to ensure users can handle them while standing upright, minimizing lumbar strain. Packages ranging from 1 to 3 kg can be allocated flexibly based on available space in the middle compartment; if full, they are assigned to the lower compartment rather than the upper compartment. Although bending is required in the lower compartment, there is no risk of falling due to standing on tiptoes, making it safer overall than the upper compartment. Light packages under 1 kg may be placed either in the upper or lower compartment to free up space in the middle compartment and meet storage needs for heavy items.

This solution only requires adjustments to allocation priorities at the backend algorithm level, without modifying cabinet hardware, resulting in extremely low implementation costs. It can also be complemented by operational guidance for couriers, requiring them to manually place heavy items on the middle layer—a supplementary measure for algorithm optimization.

(3) Human Factors Improvement of the Interactive Interface

To address touchscreen interaction challenges, improvements can be made simultaneously through hardware optimization and process simplification to significantly reduce user cognitive load. At the hardware level, replace existing mirror glass with anti-glare materials or apply anti-glare coatings to fundamentally mitigate outdoor glare; additionally, install a sunshade above the screen to block direct sunlight and enhance visibility. The screen can be adjusted to a 15-degree downward tilt angle, providing optimal viewing conditions for users ranging from 150 to 180 cm in height while alleviating glare issues for shorter users.

Button sizes have been optimized in sync with information layout. Following universal standards in human-computer interaction, the minimum size of core operation buttons has been increased to over 3.5 cm. Based on Fitts Law calculations, the optimized button's operation difficulty index stands at approximately 3.79 bits—a reduction of about 11% from current levels—effectively shortening operation time and lowering misactivation rates. The interface hierarchy has been simplified by highlighting the item retrieval function as the core process, minimizing unnecessary information interference and reducing users' visual search burden.

Additionally, a voice-assisted pickup function can be added, enabling users to input the pickup code and open the cabinet door via voice commands. This feature serves as an alternative operation method in reflective environments and helps reduce operational barriers for elderly users and individuals with limited proficiency in using smart devices.

(IV) Operational Management and Supporting Facilities

For existing cabinets already in use, large-scale hardware modifications entail significant costs; cost-effective solutions can be achieved by installing auxiliary features and optimizing operational management. A 20 cm high anti-slip footrest installed beside the cabinet effectively compensates for the height difference between women at the 5th percentile and taller users. This adjustment reduces the relative height of the top compartment's lower edge to 161 cm, making it accessible to most users. The footrest may feature a foldable design to minimize space occupation, while side handrails can be added to ensure stable center of gravity during tasks performed on tiptoe.

Tilted trays can be installed in the bottom compartments to automatically slide packages outward, reducing the bending required for users to retrieve items and minimizing trunk forward lean. This modification requires no alterations to the cabinet's main structure, is cost-effective, and yields significant benefits. From an operational perspective, a user feedback mechanism should be established to regularly collect human factor issues encountered during package retrieval, enabling targeted optimization of specific cabinet configurations. For special groups such as pregnant women or individuals with mobility limitations, a user-friendly option to prioritize middle-level compartments can be offered at the ordering interface, demonstrating operational consideration for user needs.

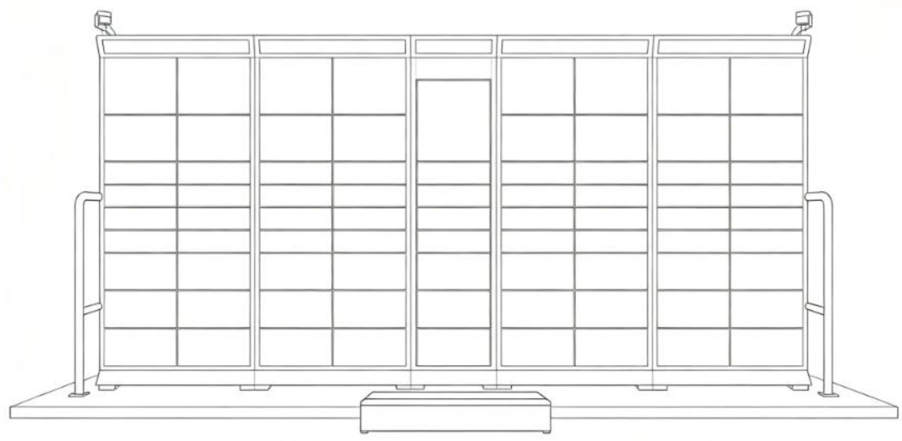

Figure 4-2: Design diagram of the footrest platform and handrail

V. Conclusion and Prospects

(1) Research Findings

This study takes the Fengchao standard smart parcel locker as the object, combining field measurement data with classic human factors tools to systematically analyze biomechanical and cognitive load issues during parcel retrieval operations, yielding three main conclusions. First, the vertical layout of the locker lacks adequate alignment with the physical dimensions of Chinese adults; the top compartment exceeds the effective reach range of most women, while the lumbar load during retrieval from the bottom compartment is elevated, with only the middle compartment exhibiting favorable human factors characteristics, indicating a structural resource mismatch overall. Second, the biomechanical risks associated with retrieval from the bottom compartment cannot be overlooked: the lifting index for a 10-kilogram package in the lowest compartment exceeds safety thresholds, and the current allocation algorithm fails to incorporate weight factors, further exacerbating health risks. Third, touchscreen interaction in outdoor settings exhibits significant shortcomings, where reflection issues combined with small button sizes increase cognitive load, particularly affecting short-statured users and elderly users.

(II) Research Limitations and Implications

This study represents an exploratory analysis at the curriculum level and still has certain limitations. The investigation focused solely on a single model of parcel lockers, and the generalizability of the conclusions requires further validation through additional case studies. Posture testing was conducted using only one sample, primarily deriving population characteristics from this limited dataset without covering diverse user groups across all age ranges. The quantitative analysis relied mainly on theoretical modeling calculations and lacked direct support from physiological experimental data such as electromyographic measurements or joint torque data. Future research should expand the sample size by recruiting participants of varying heights for controlled experiments to enhance the accuracy of the findings.

From the perspectives of engineering and management, this study offers two key insights. At the engineering design level, manufacturers of parcel lockers should adopt China's adult body size standards as core design inputs, prioritize ensuring an adequate proportion of compartments in the central comfort zone, and fully consider the unique characteristics of outdoor environments in touchscreen designs to significantly enhance user experience at a low marginal cost. At the operational management level, service providers should prioritize optimizing weight matching in allocation algorithms, combined with low-cost upgrades to auxiliary facilities, to rapidly improve the human factor performance of existing lockers. Relevant industry standards may also incorporate human factor design provisions when appropriate, guiding the sector toward more user-friendly development from a regulatory perspective.

(III) Future Research Prospects

Future related research can be advanced in three key directions. First, expand the survey scope to cover delivery lockers of various brands and usage scenarios, thereby verifying both the prevalence and variability of human factors issues. Second, employ experimental methods such as eye-tracking and surface electromyography to obtain more objective data on cognitive and muscular loads, enhancing analytical accuracy. Third, develop prototypes based on the proposed improvement solutions and conduct comparative tests to quantify optimization effects, advancing human factors research from problem diagnosis to practical implementation.

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