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Applied research using the NIOSH lifting equation to optimize the design of shopping trolley for the elderly

Chuanmei Hu✉, Xiaolin Huang, Gang Jiang, Siqi Hou & Yong Wang

In the context of an aging society, products for the elderly typically need to meet the criteria of ease of use and reduction of physical fatigue. Focusing on elderly shopping scene, combined with the ergonomic principles and JACK simulation software analysis, a method of mapping NIOSH lifting equation to the product optimization design is proposed to optimize the dimensions and styling design of the elderly shopping trolley as a carrier, to optimize length, depth, and basket height from the ground. When the handle height of the elderly shopping cart is adjustable to three levels: 795 mm, 908 mm, and 1021 mm, it can effectively reduce the pressure on the lower limbs. With a basket size of 380 mm × 340 mm × 480 mm and a ground clearance of 470 mm, the risk of lower back pain for elderly users can be significantly mitigated, enhancing the user experience of the elderly shopping cart. The optimized design of the elderly shopping cart effectively alleviates the movement burden on elderly users and provides new insights for the ergonomic optimization of other similar products.

Compared with the results of the 2010 national census, the proportion of the population aged 60 and above increased by 5.44 per cent, reaching 264 million individuals, accounting for 18.7 per cent of the total population[1]. According to international standards, China has entered an aging society, with aging-related issues spanning increasingly broad and significant domains[2]. Low Back Pain (LBP), a prevalent chronic pain among the elderly, exhibits a linear increase in incidence, with an 84 per cent incidence rate in China[3]. Guobing X et al.[4] suggested that the lifting equation proposed by the National Institute for Occupational Safety and Health (NIOSH) can serve as an indicator for assessing the risk of LBP. Linhui S et al.[5] combined questionnaires with the NIOSH lifting equation to conclude that workers experienced the most severe soreness and injury in the waist. Yali B et al.[6] utilized the NIOSH lifting equation to quantitatively evaluate ergonomic factors during lifting tasks and implemented targeted ergonomic improvements. Mohan S et al.[7] developed a system based on the NIOSH lifting equation to check whether existing working conditions comply with occupational hazards. Alkhaledi K et al.[8] designed a third-generation automatic rollover protection structure for tractors based on NIOSH principles, capable of sequentially absorbing all loads. Meepradit P et al.[9] conducted ergonomic redesigns for workers through variables of the NIOSH lifting equation, including reducing the risk of musculoskeletal disorders.

With the increase in the elderly population and their emphasis on health, there should be a greater output of products for the aging population. However, among the over 60,000 aging-related products globally, China accounts for only 10 per cent[10]. There is a significant asymmetry between supply and demand in the aging industry market in China in terms of market research and development. All try to support aging in place so that independence, freedom of choice and life style are promoted[11], yet the needs of the elderly remain far from being fully met. According to the results of The Seventh National Census, 87.2 per cent of the elderly have the ability to take care of themselves[12]. Shopping is one of the most important travel purposes for the elderly, accounting for over 48 per cent[13,14]. The entire shopping process involves actions such as pushing, pulling, and bending, with an item requiring retrieval four or more times, Fig. 1 illustrates the shopping process. Dongmei Y et al.[15] proposed a design scheme for elderly shopping carts based on user needs and verified its feasibility using a mathematical fuzzy evaluation method. Hesen L et al.[16] proposed a shopping cart service system from the perspective of the "thing system." Yaxuan S et al.[17] considered the handles and wheels from an ergonomic perspective. Sales, J et al.[18] proposed a person-following shopping cart and assistant robot to help the elderly carry products in supermarkets. Soori, P.k. et al.[19] explored the mapping relationship between design factors of elderly shopping

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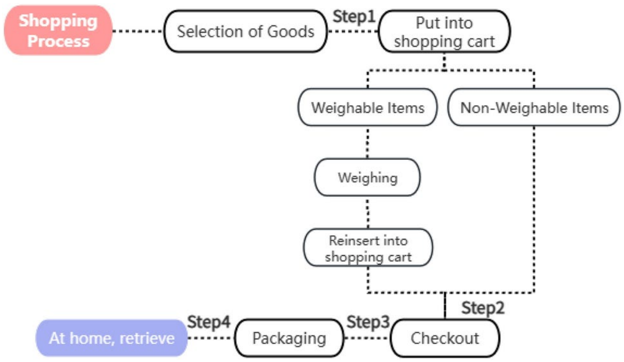

Fig. 1. Shopping flowchart.

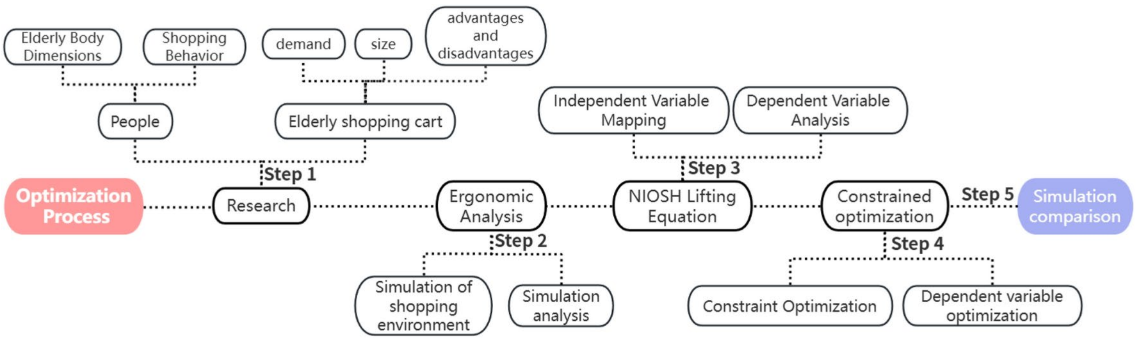

Fig. 2. Optimizing the design process framework.

carts and user perception imagery by introducing the Miryoku engineering theory to guide innovative designs of elderly shopping carts.

In related research, most scholars have assessed product feasibility from the subjective perspective of users, while there are fewer studies that conduct quantitative evaluations based on objective physical harm. Psychologist Donald Norman categorizes user experience into three levels: visceral, behavioral, and reflective[20]. This paper focuses on user behavior, examining the movement patterns of elderly individuals during shopping activities and exploring their visceral and behavioral aspects in this context. Taking the most widely used elderly shopping cart on the market as a control, the study employs the JCAK ergonomics simulation software to simulate shopping movements. By applying the NIOSH lifting equation to the design of elderly shopping carts, the paper proposes adjustment strategies for the handle height and basket size of elderly shopping carts. Comparative analyses with the control group reveal shortcomings in the dimensional design of existing elderly shopping carts. This study enhances the ergonomics analysis of elderly shopping carts and proposes corresponding optimization design strategies for existing products, providing new insights into the ergonomic optimization of similar products.

Results

Optimization ideas

Map the independent variables of the NIOSH lifting equation to dimensions of the elderly shopping trolley were. Ergonomic analysis of the actions involved in the shopping activity using 3D simulation software. Jack 8.0.1 and Rhino 7 were used as tools, to model and import the shopping trolley and the digital human body, construct the shopping activity simulation scenario, and perform dynamic simulation of the shopping activity to achieve the operation and analysis of the actions. The simulation process comprises three evaluation modules: Lower Back Analysis (LBA), NIOSH lifting analysis (NLA), and Reach Zones Analysis (RZA). The optimal values of the dependent variables are obtained through analytical equations and constrained optimization methods. The effectiveness of the optimized NIOSH lifting equation in reducing human fatigue and enhancing user experience is analyzed and verified in conjunction with ergonomics theory. Figure 2 illustrates the process of optimising the design

Optimization methodology

In the preceding section, we primarily divided the optimization process into five steps: research, acquisition of simulation preset parameters, optimization analysis using the NIOSH lifting equation, constrained optimization, and simulation comparison. These five steps constitute a systematic and comprehensive framework for design optimization, employing scientific methodologies to ensure that the design of shopping carts for the elderly aligns with ergonomic principles and effectively enhances their shopping experience. Below is a detailed elaboration of each step in the article.

(1) Research: This step is divided into three subprocesses. Through research on the anthropometric dimensions of the elderly, shopping behaviors, and existing products, we aim to understand the underlying purposes of user behaviors and the deficiencies of current products, selecting the target for optimization analysis. Based on the psychological and physiological needs of the elderly, suggestions for product operation, design, and color are proposed to enhance the user experience.

(2) Acquisition of Simulation Preset Parameters: Force analysis is conducted on the target object, simplifying structures that do not influence the outcome. Subsequently, a simulated scenario is constructed based on the shopping behaviors of the elderly to acquire simulation preset parameters, which serve as comparison benchmarks for later product optimization validation.

(3) NIOSH Lifting Equation: The meanings of the independent and dependent variables in the equation are analyzed, with the mapped meanings of the independent variables in the shopping process being extracted. The implications and trends of the dependent variables are also analyzed.

(4) Constrained Optimization: Combining constrained optimization methods, the corresponding values of the independent variables are derived through analysis of the dependent variables. Finally, by regressing to the mapped meanings, the optimal dimensions for shopping carts for the elderly are obtained.

(5) Simulation Comparison: The optimal dimensions derived from the above analysis are compared with the simulation preset parameters. A comparative analysis is conducted before and after optimization to verify the effectiveness of the NIOSH lifting equation in optimizing shopping carts for the elderly.

Simulation environment setup

The factors affecting shopping behavior of the elderly are mainly human, machines and environment[21]. Using JACK simulation software to simulate shopping activities, five action modules were designed for grasping, pushing, pulling, picking up and placing commodities. A digital human body model was established based on the anthropometric data of 61–70-year-olds in GB/T 10000-2023, as presented in Table 1. According to the market research, the size range of existing shopping trolleys for the elderly is 260 mm–650 mm × 350 mm–500 mm × 860 mm–960 mm, with basket sizes ranging from 200 mm–480 mm × 250 mm–420 mm × 400 mm–550 mm. The application of Rhino software to on the market is the most widely used one of the senior citizen shopping trolley 1:1 modeling, the model is simplified without affecting the analysis results to improve the simulation efficiency, as shown in Fig. 3. Since bending is greater below waist height, the damage to the human body caused by the action of picking up commodities from the bottom of the shopping trolley was mainly analyzed and simulated. The created digital human and the simplified model were placed into the simulated shopping environment, and the human action posture was adjusted using the human control window. The action animation of the shopping activity was created with five action modules of retrieve, push, putting, grasping and pulling, as shown in Fig. 4 (P5 of female as an example)

In both the pushing and pulling postures, functional hand height (axis of grip) affects the inclination between the human hand and the pull rod. The paper assume an angle of 65° between the lever and the ground when pushing the shopping trolley. The angle between the lever and the ground when pulling the shopping trolley needs to be adjusted according to different heights. For a P5 female, the proposed angle between the lever and the ground when pulling the shopping trolley is 35°. Figures 5 and 6 show the force analysis of points A, B, and C, which represent people, objects, and wheel force points. F1 and F3 are required to overcome the force of gravity upwards, while F2 and F4 are required to overcome the friction force from the ground, respectively. This the paper selects home shopping trolley wheels made of PU material, which have a coefficient of rolling friction on the ground of 0.02.

$$F_1 = x_1 G / x_2 \tag{1}$$

$$F_2 = F_4 = F_f = \mu G / 2 \tag{2}$$

According to the formula of (1), (2), the forces at different functional hand height were calculated, and the weight loads were added to the force points of the digital human model to analyze the forces on the lower back during different movements. The experimental animation collected data of LBA, NLA, and RZA at different movements.

	Female			Male		
Percentile	**P5**	**P50**	**P100**	**P5**	**P50**	**P100**
Height (mm)	1450	1541	163	1545	1652	1751
Weight (kg)	45	59	76	51	65	83
Shoulder height (mm)	1171	1252	1338	1265	1353	1451
Elbow height (mm)	871	939	1010	937	1015	1097
Maximum shoulder width (mm)	377	409	448	404	440	475
Hand length (mm)	158	170	182	170	183	197
Hand width (mm)	74	81	88	80	88	96

Table 1. Elderly body dimensions.

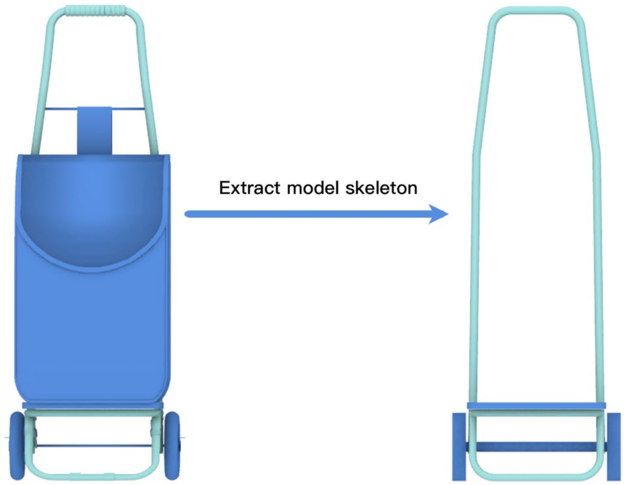

Fig. 3. Simplification process of elderly shopping cart model.

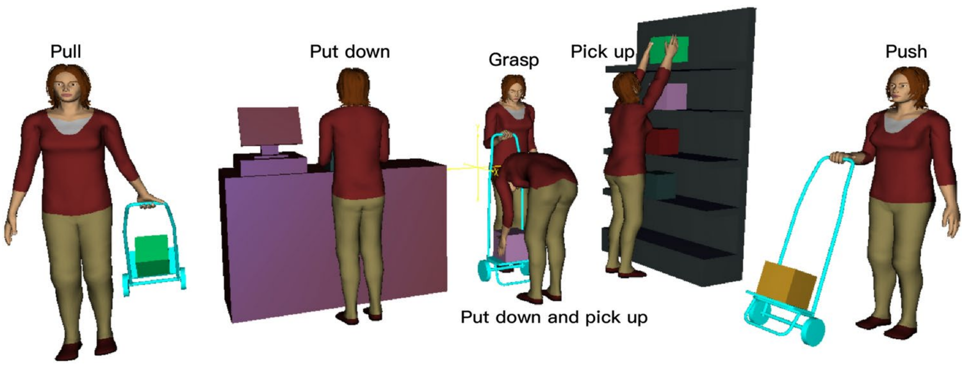

Fig. 4. Shopping actions and environment.

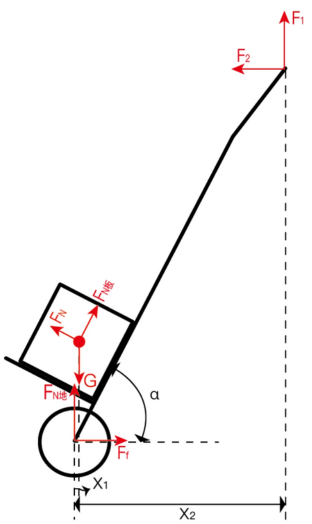

Fig. 5. Force analysis (push).

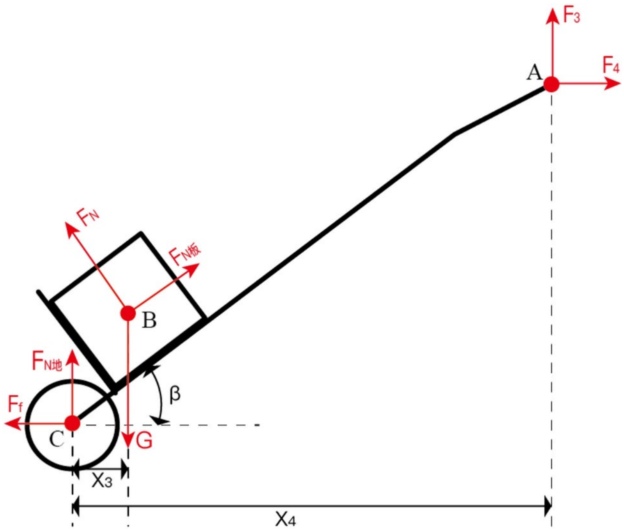

Fig. 6. Force analysis (pull).

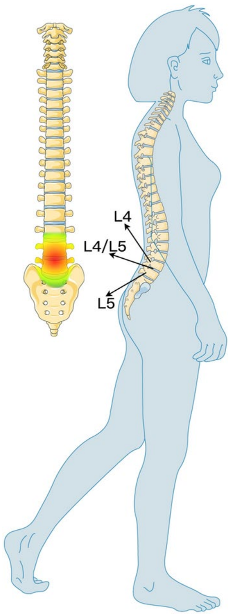

Fig. 7. The spinal L4/L5.

Simulation predefined parameter analysis

Lower back analysis (LBA)

LBA helps you evaluate the spinal forces acting on a virtual human's lower back, under any posture and loading condition. It assesses the forces on the L4/L5 lumbar spine when the virtual human is performing work[22], To help guide the design in order to reduce the risk of injuries, and the L4/L5 position is shown in Fig. 7. The paper collects lower back pressure values based on existing shopping trolley for older adults during shopping activities such as grasping, pulling, pushing, and picking up commodities from the trolley. The likelihood of lower back injury increases with higher values. If the value exceeds 3400N proposed by NIOSH, there is a possibility of lower back disorders.

Based on the previous survey on shopping behavior among the elderly, it was found that users tend to pull the shopping trolley while shopping. This phenomenon is confirmed by simulation results, which show that pulling the shopping trolley puts less pressure compared with pushing on the lumbar spine. Different actions do not have a significant effect on the lower back pressure of different percentiles, but L4/L5 is higher for males

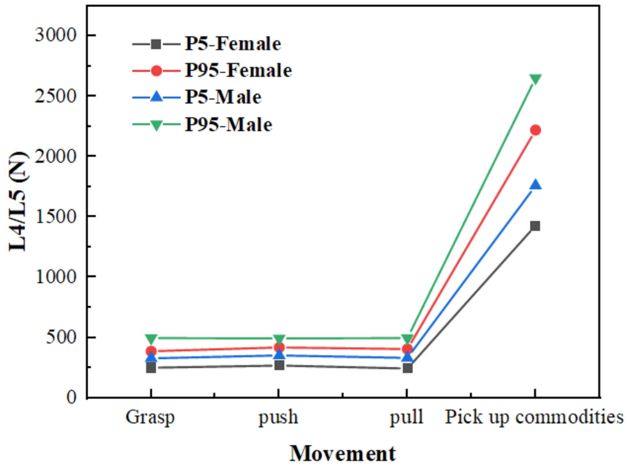

Fig. 8. Force of L4/L5 under different movements.

Movement	LI	RWL (kg)	CLI
① Placing commodities in the shopping cart	0.58	10.41	1.124
② Removing weighed commodities	0.60	11.06	
③ Putting back the weighed commodities	0.49	12.15	
④Taking out to checkout	0.60	11.06	
⑤ Putting back in the shopping cart	0.49	12.15	

Table 2. Shopping behavior NIOSH analysis.

than females at the same percentile. The lumbar pressures were within reasonable limits for all four maneuvers: grasping, pushing, pulling, and picking up commodities, as shown in Fig. 8.

NIOSH lifting analyses (NLA)
The NLA assesses the safe weight or load that can be lifted in a given position and time frame. Specifically, the Recommended Weight Limit (RWL) is the weight of the load nearly all healthy workers can be expected to handle over a reasonable period of time (not to exceed eight hours) without increasing the risk of developing lift-related low back pain. The lifting index (LI) is a relative estimate of the level of physical stress associated with a manual lifting task. The lifting index compares the actual weight of the load for a given task with the recommended weight. The greater the LI, the greater the risk of low back pain. The paper analyses five shopping processes in the pair shopping process. The NIOSH lifting equation are independent of height and weight parameters, resulting in identical simulation results for both male and female. The simulation results are presented in Table 2.

Based on the simulation analysis results, it is evident that each action's LI<1, which indicating that it is body-friendly. However, combined the all activities together, CLI>1, which may increases the risk of LBP. RWL within the range from 10.41 kg to 12.15 kg.

Reach zones analysis (RZA)
The RZA tool describe the maximum and comfortable coverage area of the digital human, ensuring the target population has full access to the necessary components of the product to accomplish operational tasks more conveniently. To analyses the ease of access to commodities from the back of a shopping trolley for elderly individuals, using spherical data. The reachable domain analysis is conducted on P5 of females and P95 of males to validate the rationality of size the shopping trolley basket for the elderly.

According to the results (Fig. 9), the P95 of male and P5 of female are unable to reach products at the bottom of the shopping trolley when bending at 60° and 30° respectively. As a result, they have to remove products from the side or front of the trolley, which reduces shopping efficiency. The shortest straight-line distance from the floor was measured to be approximately 5100 mm using the 'Measure Distance' tool.

Optimization design

Man-machine size analysis
Using ergonomics as the theoretical basis, the NIOSH lifting equation's variables were applied to the design of a senior shopping trolley. To limited the range of independent variable values and combined them with the constrained optimization method to obtain an optimal solution.

According to industrial designer Henry Dreyfuss, the most comfortable height for human body is 76 mm below the height of the human elbow. Therefore, the handle heights of shopping trolleys for male at the 5th,

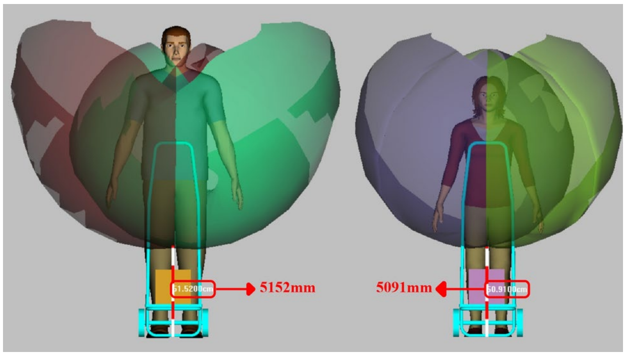

Fig. 9. Reach zones analysis.

Limiting quantity	Meaning in the NIOSH lifting equation	Significance of mapping	Range of values
LC	Load constant	–	23 kg
H	The horizontal distance from the center of the palms to midway between the ankle joints	1/2 the length of the basket + the horizontal distance between the two ankle joints from the basket	300–540 mm
V	The vertical distance from the v hands to the floor	Optimal hand position height	200–1000 mm
D	The vertical distance from the start and end of the lift	Shopping trolley basket height	400–900 mm
FM	Frequency parameter of the lift	Number of times object was grasped	8 times per hour
A	Angle of deviation from the sagittal plane	Body rotation angle	0
CM	Parameters for easy object grasping	The difficulty of grasping items	1

Table 3. Meaning and range of limiting values.

Condition	H (mm)	V (mm)	D (mm)	LI	RWL (kg)
Most comfortable	300	750	400	0.336	17.873
Maximum volume	390.6	710	480	0.451	13.290

Table 4. Optimized data.

50th, and 95th percentiles are 861 mm, 939 mm, and 1021 mm, respectively, respectively, the handle heights for female at the 5th, 50th, and 95th percentiles are 795 mm, 863 mm, and 934 mm, respectively. This means that the handle heights of shopping trolleys for senior citizens range from 795 mm to 1021 mm, which can be adjusted to three different levels: 795 mm, 908 mm, and 1021 mm, and the height of each gear is 113 mm, to feature caters to individuals with varying needs. The most comfortable grip diameter is between 30 mm and 40 mm, and an oval shape is preferred as it increases the contact area between the handle and the hand, providing better grip and support to the wrist. In addition, the shopping trolley's width should not exceed the maximum shoulder width of the human body (377 mm), to improve portability of operations.

NIOSH lifting analysis (NLA)

The NIOSH lifting equation are determined LC, H, V, D, FM, A, and CM. The specific formulas, meanings, and value ranges for these argument are shown as formula (3), (4) and Table 3. Based on the survey of existing shopping trolleys, combines with the significance of the independent variables in the lifting equation is to limit value ranges.

$$\text{RWL} = \text{LC} \times \frac{25}{H} \times (1 - 0.003|V - 75|) \times \left(0.82 + \frac{4.5}{D}\right) \times (1 - 0.0032 \times A) \times FM \times CM \tag{3}$$

$$LI = \frac{Actual - task - load - weight}{RWL} \tag{4}$$

Upon analysis of the formula, it is observed that when H and D take the minimum and V is 75, the RWL attains its maximum value, at the same time LI is minimized, using the constraint optimization method. Set the independent variable restriction conditions, so as to get in the case of RWL as large as possible, can allow the maximum volume conditions of the independent variable value, so that the space utilization of the elderly shopping trolleys to get the maximization of the results of the analysis as shown in Table 4.

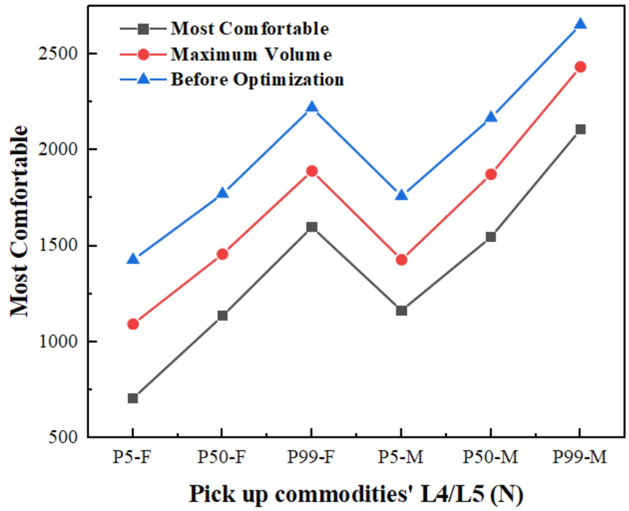

Fig. 10. Comparison of L4/L5 optimization.

	Before optimization			Most comfortable			Maximum volume		
Movement	**LI**	**RWL**	**CLI**	**LI**	**RWL**	**CLI**	**LI**	**RWL**	**CLI**
① Placing commodities in to shopping cart	0.58	10.41		0.57	10.57		0.57	10.52	
② Placing commodities in to shopping cart	0.60	11.06		0.37	16.41		0.39	15.48	
③ Removing weighed commodities	0.49	12.15	1.124	0.45	13.25	0.959	0.47	12.82	0.982
④ Putting back the weighed commodities	0.60	11.06		0.37	16.41		0.39	15.48	
⑤ Taking out to checkout	0.49	12.15		0.45	13.25		0.47	12.82	

Table 5. Comparison of NIOSH optimization for different movement.

Product function optimization
In design, it is essential to clarify the functional attributes of the product so that auxiliary functions serve the main function[23]. The handle and grip should be made of soft material with anti-slip properties, such as rubber or PU. The raised geometry of the palm area can reduce fatigue in the palm and wrist. Secondly, the elderly have relatively low physical mobility and hand strength. Therefore, the foot brake is more suitable for their needs. Additionally, anti-skid wheels maintain stability and grip on different surfaces, reducing unnecessary bumps and strain on the arms and lower back. Finally, a seat or cushion provides support and reduces fatigue when walking for long periods.

Comparison of LBA
When using a shopping trolley, elderly individuals are usually in an upright state during grasping, pushing and pulling, which reduces the risk of excessive force on the lower back. The paper employs LBA to analyze the action of picking up commodities from an optimized shopping trolley for the elderly. The L4/L5 forces before optimization are compared and analyzed, as shown in Fig. 10

The comparison demonstrates that the optimization can significantly decrease the force on the lower back. Specifically, the force can be reduced by approximately 600N in the most comfortable scenario and about 300N under the maximum volume scenario.

NIOSH analysis comparison
The LI, RWL and CLI of the two sizes, the most comfortable and the largest volume at the time of the five shopping trips were simulated and the simulated parameters were compared to validate the optimization results. The simulation Table 5 show that the CLI <1 after optimization, indicates reduced pressure and load on the human body during shopping activities. The optimized size effectively control and manages to human load aspect of shopping activities, reducing muscle fatigue and the risk of injuries. Improves the health and safety of the elderly when shopping.

Reachability analysis comparison
As shown in Fig. 11, after optimization, the shopping trolley allows the elderly to easily reach products at the bottom of the basket and retrieve them more conveniently. Additionally, the lowest handle position allows P5 of female to bend down 60°, reducing the height of fingertips from the ground by 10cm and improving the shopping trolley's convenience for the elderly.

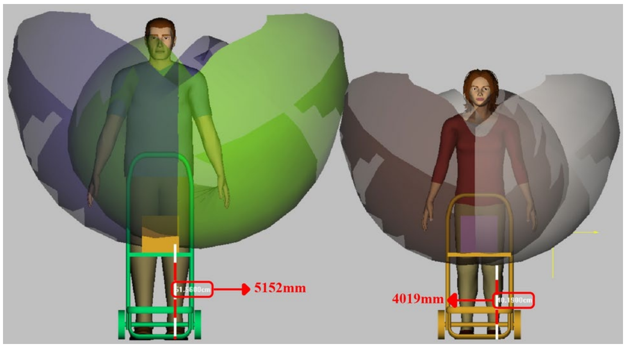

Fig. 11. Simulation of reachable workspace after optimization.

Conclusions

This paper applies the National Institute for Occupational Safety and Health (NIOSH) lifting equation to the design optimization of shopping carts for the elderly, aiming to alleviate low back pain (LBP) caused by frequent bending and rising during shopping activities. Virtual experiments and in-depth analyses were conducted using JACK simulation software. We analyzed the lumbar spine forces, NIOSH lifting indices, recommended weight limits, and reachable zones for elderly individuals during shopping. The results indicated that when the shopping cart handle heights were set at three different levels (795 mm, 908 mm, and 1021 mm), it effectively reduced the stress on the lower limbs, increased the interaction space between humans and the cart, and enhanced operational comfort. When the basket dimensions were 200 mm × 340 mm × 400 mm and positioned 550 mm above the ground, the lumbar spine force of elderly users was reduced by approximately 600 N; with basket dimensions of 380 mm × 340 mm × 480 mm, the reduction was about 300 N. These configurations not only ensured comfort but also improved product utilization and increased usable space. Additionally, the comprehensive lifting indices of the optimized shopping carts for the elderly were all below 1, indicating that the optimized design effectively safeguarded the health and safety of elderly users during shopping. Meanwhile, the recommended weight limits after optimization were increased, allowing elderly individuals to carry heavier items under the same conditions, thereby enhancing shopping efficiency.

In summary, this paper demonstrates the effectiveness of applying the NIOSH lifting equation in product design through a case study on shopping carts for the elderly. It not only provides optimization strategies for the design of shopping carts for the elderly but also opens up new ideas for design research in other related fields.

For data citations of datasets uploaded to e.g. *figshare*, please use the howpublished option in the bib entry to specify the platform and the link, as in the Hao:gidmaps:2014 example in the sample bibliography file.

Data availability

All data generated or analysed during this study are included in this published article.

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Declarations

Competing interests
The authors declare no competing interests.

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