Modular and Customizable Schoolbag Carrying System for Primary School Students: Optimization and Validation Based on Pressure Distribution Experiments

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Abstract. Primary school students aged 7–12 are in a critical stage of spinal and musculoskeletal development, yet most commercially available schoolbags still adopt standardized sizes that cannot adequately accommodate children's substantial body-type differences. This mismatch often leads to concentrated pressure on the shoulders and waist, increasing the risk of discomfort and long-term postural problems. To address this issue, this study proposes a modular and customizable schoolbag carrying system for primary school students based on pressure distribution experiments. First, anthropometric measurements were conducted to identify key body-type characteristics related to schoolbag fit. Then, the carrying system was decomposed into three core support modules, including back, waist, and shoulder components, and their dimensional parameters were optimized through pressure distribution testing. Based on the experimental results, a body-type-to-module mapping strategy was established. Finally, a modular prototype was developed and compared with a conventional schoolbag under static standing and dynamic walking conditions. The results showed that the proposed system improved pressure distribution, reduced local high-pressure concentration on the shoulders and waist, and enhanced fit for children with different body types. The study demonstrates that integrating anthropometric stratification, pressure-based optimization, and modular design can provide an effective approach for developing ergonomic schoolbags with both personalization and mass-production potential.

Keywords: children's schoolbag; ergonomics; modular design; pressure distribution; body-fit adaptation.

1 Introduction

Children's schoolbags play a critical role in daily load carriage, yet conventional designs often fail to accommodate the diverse body characteristics of primary school students[3]. Improper fit and uneven load distribution can lead to localized high pressure, discomfort, and potential long-term spinal issues[1]. Existing ergonomic or 'spinal-pro

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tective' schoolbags typically rely on fixed specifications or coarse height-based classifications, which cannot adequately address variations in height, shoulder width, back length, or BMI among children of the same age group.

To address this limitation, modular designs that allow body-type-specific adaptation have been proposed [2]. However, most existing modular schoolbags focus on storage or aesthetics rather than the carrying system itself, and few studies provide quantitative evidence linking body parameters, support-module design, and ergonomic outcomes. There remains a need for a practical approach that can balance individualized fit and manufacturability.

In this study, we propose a modular customizable schoolbag design based on body-type stratification and pressure distribution experiments. The study integrates anthropometric analysis, experimental optimization, and prototype validation to provide a practical pathway for ergonomic and adaptable schoolbag design.

2 Methods

2.1 Anthropometric Measurement and Body-Type Stratification

Standardized anthropometric measurements were conducted on primary school students aged 7–12. According to Human Dimensions of Chinese Minors (GB/T 26158-2010), height, weight, shoulder width, and back length were measured, and BMI was calculated from height and weight. Each parameter was measured three times and averaged for analysis. Based on the measurement results, a body-type stratification framework was established with height, shoulder width, and BMI as the core variables, providing the basis for subsequent support-module optimization.

2.2 Module Optimization and Prototype Development

Based on the stratification framework, the schoolbag was decomposed into three core modules: back, waist, and shoulder. Pressure distribution experiments were conducted to optimize key dimensional parameters using the SPI Tactilus flexible pressure sensing system [4,5]. The modular schoolbag prototype was then fabricated with a general bag body and replaceable support modules.

2.3 Validation Experiment

To evaluate the effectiveness of the proposed design, a self-controlled comparative experiment was conducted between the modular customizable schoolbag and a conventional commercially available schoolbag under static standing conditions. Objective pressure data were collected using the flexible pressure sensing system, and subjective ratings were used to assess shoulder comfort, back support, waist comfort, and overall comfort. A self-controlled comparative experiment evaluated the modular schoolbag against a conventional schoolbag under static standing conditions. Objective pressure data and subjective ratings were collected.

3 Results

3.1 Body-Type Stratification Results

Anthropometric measurements revealed substantial variability in height, shoulder width, back length, and BMI among children aged 7–12. Analysis of these data identified 140 cm as a critical height threshold, dividing the sample into children with height <140 cm and ≥140 cm. Differentiated BMI thresholds were set to classify overweight children, with BMI ≥19 for the <140 cm group and BMI ≥22 for the ≥140 cm group. Shoulder width was identified as another key parameter for module design, with 26.5 cm serving as the reference threshold.

Based on these variables, the study established a body-type stratification framework using height, shoulder width, and BMI. In practice, this framework generated eight body-type groups through the combination of two height categories, two shoulder-width categories, and two BMI categories. This level of classification was sufficient to reflect major differences in children's carrying-related body characteristics while remaining limited enough for practical manufacturing and product configuration. The body-type framework therefore provided the basis for the subsequent parameter optimization and module-matching strategy.

3.2 Optimization Results of the Core Support Modules

Based on the body-type stratification framework, pressure distribution experiments were conducted on the back, waist, and shoulder support modules to determine optimal parameters. The results showed that children with different body types responded differently to module dimensions, confirming the need for body-type-based optimization.

For the back support module, a 16 cm pad was optimal for children with height <140 cm, while a 20 cm pad was best for those ≥140 cm. Thickness was set at 2 cm for both groups. The waist support module achieved the best overall fit and pressure distribution with a length of 10 cm. Thickness was 2 cm for normal BMI children and 1 cm for high BMI children. For the shoulder support module, a 7 cm width × 1 cm thickness combination provided the best overall performance and was selected as a universal configuration.

The final optimal parameter combination is summarized in Table 1. These results indicate that optimal support parameters vary across body types, supporting the rationale for a modular approach that allows differentiated adaptation.

Table 1. Optimal parameter combination of the modular support system

Support Module	Structural Parameter Type	Optimal Parameter Value
Back Support Module	Length	Below 140 cm: 16 cm; 140 cm and above: 20 cm
	Thickness	2 cm (applicable to all body types)

Lumbar Support Module	Length	10 cm (applicable to all body types)
	Thickness	Normal BMI group: 2 cm; High BMI group: 1 cm
Shoulder Support Module	Width	7 cm (applicable to all body types)
	Thickness	1 cm (applicable to all body types)

3.3 Results of Modular Schoolbag Design and Prototype Fabrication

Based on the body-type stratification and optimized module parameters, a modular customizable schoolbag prototype was developed. The design combined a general bag body with replaceable back, shoulder, and waist support units. As shown in Fig. 1, the prototype retained the overall form and functional requirements of a conventional schoolbag while incorporating the modular carrying system.

To balance fitting accuracy and manufacturing feasibility, the system was organized around a limited number of module families, including two back-panel specifications, two back support modules, one shoulder support module, two waist support modules, and two shoulder-strap width options, which were used to match the eight body-type groups derived from height, shoulder width, and BMI. During fabrication, structural integration and sample production were completed, resulting in a physical prototype suitable for validation experiments (Fig. 2). The modular system was designed so that both parents and children could complete module replacement through simple operations. In addition, the design did not add an extra support layer, but transformed the original support units into replaceable components, so adaptability was improved without intentionally increasing the structural weight of the schoolbag.

Fig. 1. Modular schoolbag prototype design integrating back, shoulder, and waist modules

3.4 Static Validation Results of the Modular Prototype

After module optimization and prototype fabrication, a self-controlled comparative experiment was conducted to evaluate the modular schoolbag against a conventional commercially available schoolbag under static standing conditions. Eight children participated, covering representative body-type combinations across the stratified groups. The modular schoolbag outperformed the conventional schoolbag in both objective pressure and subjective comfort evaluations.

For the height <140 cm group, the average pressure reduction was 24.5% and the maximum pressure reduction was 28.1%. For the height ≥140 cm group, the average pressure reduction reached 26.5%, and the maximum reduction reached 47.6%. Older overweight children experienced maximum pressure reductions exceeding 50% in the shoulders and waist. As shown in Fig. 2, the modular design effectively redistributed load and reduced localized pressure concentration. Subjective evaluations (Table 2) also showed higher ratings for shoulder comfort, back support, waist comfort, and overall comfort, with an overall subjective improvement of 78.6%. These results support the short-term effectiveness of the modular system in improving fit and pressure distribution under static conditions, although pressure indicators in this study should be understood as proxy measures rather than direct long-term health outcomes.

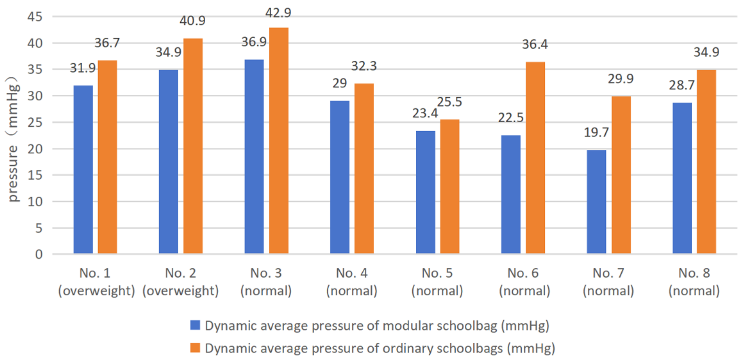

Fig. 2. Static pressure performance comparison between modular and conventional schoolbags

Table 2. Subjective evaluation results for the modular and conventional schoolbags

Evaluation Dimension	Mean Score of Modular Customizable Schoolbag	Mean Score of Conventional Schoolbag	Paired-sample t value	p value	Subjective Improvement Rate (%)
Shoulder Comfort	4.25	2.38	5.892	0.011	78.6
Back Support	4.38	2.25	6.437	0.012	94.7
Waist Comfort	4.13	2.13	5.314	0.009	93.9
Dynamic Stability	4.00	2.50	4.243	0.006	60.0
Overall Comfort	4.25	2.30	5.892	0.002	78.6

4 Discussion and Conclusion

This study shows that the ergonomic performance of children's schoolbags depends on the overall matching between carrying-system parameters and body characteristics, rather than only on the optimization of individual components. By using height, shoulder width, and BMI for body-type stratification, the proposed modular design provided more targeted adaptation than conventional fixed-specification schoolbags, and the improved static pressure performance and subjective comfort ratings indicate better short-term carrying conditions.

At the same time, the pressure maps and pressure indices used here were proxy indicators of carrying performance rather than direct evidence of long-term posture correction or reduced back-pain incidence. Therefore, the present study supports short-term pressure improvement, while the relationship between pressure reduction and long-term musculoskeletal benefits still requires longitudinal verification. In practical terms, the proposed system was designed to remain manageable in use and production: eight body-type groups were matched using a limited number of standardized modules, and module replacement was intended to be simple enough for both parents and children as body characteristics change. Moreover, the modular design did not add an extra support layer, but converted the original support structure into replaceable components, aiming to improve adaptability without substantially increasing bag weight. Overall, the results suggest that modularization provides a practical pathway to combine differentiated fit, controlled product complexity, and ergonomic improvement in children's schoolbags.

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