

Mechanical Behavior Analysis of Structures and Shape Optimization for Novel Continuous Passive Motion Device with Abduction Function

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In this study, we propose a systematic design methodology to address the conflicting multi-objective optimization problem of balancing structural strength and weight reduction for a novel continuous passive motion (CPM) rehabilitation aid. The research was conducted in two phases. First, a finite element analysis (FEA) model was established and experimentally validated using displacement measurements obtained from a displacement transducer and sensor interface, thereby ensuring that the numerical model accurately reflected the structural behavior of the physical CPM device. Second, the Taguchi method and grey relational analysis were systematically applied to consolidate maximum equivalent stress and weight into a single performance index, thereby achieving a balanced evaluation. The Taguchi results confirmed the factor influence ranking ($D > B > C > A$) and identified the optimal design parameter combination as A2B1C2D3. The optimized design achieved a 55.5% reduction in maximum stress compared with the baseline design and a 15% reduction in weight. The subsequent FEA results demonstrated that the maximum equivalent stress of the optimized design was significantly lower than the yield strength of the material, thereby confirming structural safety. Furthermore, the results confirmed that the selected design factors significantly affected overall performance and that strong interaction effects existed among them. Overall, the proposed optimization framework effectively balanced structural strength and weight reduction, providing a practical reference for the structural design of rehabilitation devices.

1. Introduction

The accelerating trend of an aging population in Taiwan has led to a significant increase in the prevalence of limb dysfunction resulting from diseases or trauma, consequently driving up

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the demand for effective rehabilitation treatments. The continuous passive motion (CPM) device serves as a vital rehabilitation aid, enabling patients to passively perform joint movements post-surgery or injury, thereby effectively preventing joint contracture and stiffness. Recent studies have highlighted the effectiveness of advanced robotic systems, such as the Hybrid Assistive Limb, in improving gait kinematics and functional recovery after major orthopedic procedures such as total knee arthroplasty and in early postoperative care for hip fractures.^(1–3)

However, most existing commercial CPM devices offer relatively limited functionality, often failing to meet complex rehabilitation requirements. Addressing this limitation, in this study, we developed a novel CPM device that incorporates an abduction function. This enhanced design not only facilitates fundamental flexion and extension motions but also incorporates hip joint abduction,⁽⁴⁾ providing a more comprehensive rehabilitation approach compared with conventional CPM devices, particularly for patients recovering from procedures such as total hip arthroplasty.⁽⁵⁾

A key challenge in designing such medical aids is achieving a balance between structural integrity, which ensures sufficient strength to safely support the user's limb, and lightweight construction, which enhances portability and usability. Previous studies on robotic and rehabilitation devices have addressed structural design from different perspectives. Lightweight structural design has been investigated through topology optimization in robotic components.⁽⁶⁾ Lower-limb rehabilitation robots have also been evaluated in terms of mechanism design, kinematic performance, workspace, and structural feasibility.⁽⁷⁾ In addition, static and modal analyses have been employed to assess the structural and vibration characteristics of wearable lower-limb rehabilitation robots.⁽⁸⁾ These studies demonstrate the diverse structural requirements and evaluation approaches adopted for robotic and rehabilitation systems. In contrast, the present study focuses specifically on the structural optimization of an abduction-enabled CPM device, in which maximum equivalent stress and device weight are simultaneously considered using an integrated finite element analysis (FEA)–Taguchi–grey relational analysis (GRA) framework.

Since structural strength and weight reduction are often conflicting design objectives, a systematic approach is necessary for multi-objective optimization. Integrated optimization approaches combining the Taguchi method, FEA, and GRA have been applied to structural design problems, with displacement measurements further employed for experimental validation.⁽⁹⁾ Sensor-based technologies have also been integrated into lower-limb rehabilitation robots to detect patient-related biosignals and support rehabilitation control.⁽¹⁰⁾ The primary aim of this research is therefore to establish a systematic methodology for the multi-objective optimization of the structural strength and weight of the proposed abduction-enabled CPM device. In the present study, displacement sensing was employed to experimentally quantify the structural response of the physical CPM device and validate the numerical model used for subsequent structural optimization. Specifically, the research objectives are as follows.

- (1) To establish a numerical model of the CPM device under flexion and extension loading conditions using FEA via ANSYS Workbench and to validate its reliability and accuracy through sensor-based displacement measurements obtained from the physical device
- (2) To systematically evaluate the effects of various design parameters on the structural strength and weight of the device by employing the Taguchi method for experimental design combined

- with GRA, thereby identifying the optimal parameter combination
- (3) To utilize the integrated methodology to optimize the CPM device in terms of both structural strength and weight

2. Methodology

In this study, we propose a systematic two-stage multi-objective optimization methodology for the novel abduction-enabled CPM device. The first stage involved numerical modeling and experimental validation using FEA, thereby establishing a reliable analytical model. The second stage involved multi-objective optimization, in which the validated model was integrated with the Taguchi method and GRA to systematically determine the optimal design parameters for achieving both high structural strength and weight reduction.

2.1 Design of CPM device

The developed rehabilitation aid is a CPM device that features an abduction function. Driven by a servo motor, the device provides precise motion across a flexion range of 90 to 180° and an abduction range of 0 to 30°. This specific abduction capability represents a key advantage over conventional commercial models, providing a more comprehensive rehabilitation approach. Structurally, the design balances these functional motion requirements with the concurrent need for structural strength and weight reduction. The structural analysis and optimization focused primarily on the device's core mechanism during flexion and extension to ensure stability and safety under load. Figure 1 illustrates the CPM device in the flexion state and Fig. 2 shows the abduction state.

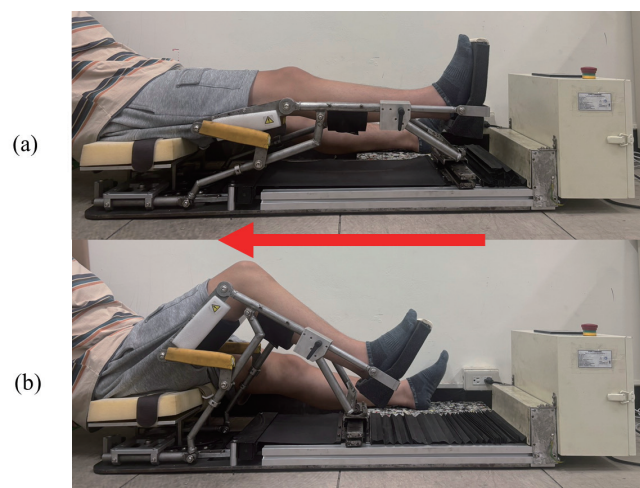


Fig. 1. (Color online) Lower-limb positioning on CPM device at different flexion angles: (a) 180 and (b) 90°. The red arrow indicates the linear movement direction of the supporting mechanism from the 180 to 90° flexion state.

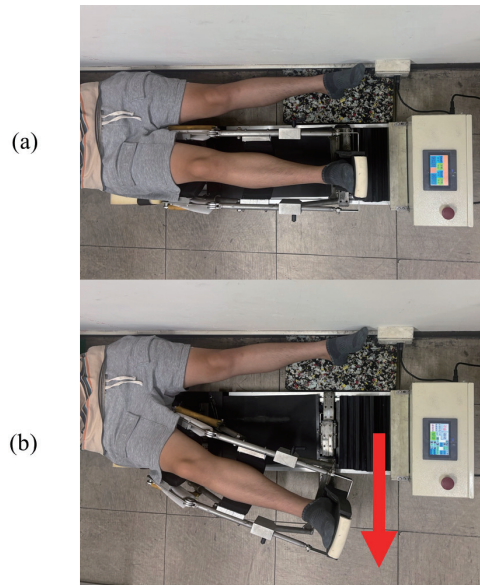


Fig. 2. (Color online) Lower-limb positioning on CPM device at different abduction angles: (a) 0 and (b) 30°. The red arrow indicates the movement direction of the device from the 0 to 30° abduction state.

2.2 Finite element analysis

In this study, we used ANSYS Workbench to perform FEA and obtain structural strength and weight data for the subsequent Taguchi method and GRA. The numerical model was constructed using SolidWorks and then imported into ANSYS for structural analysis. To enhance computational efficiency and accuracy, the model was simplified by removing transmission mechanism configurations that did not significantly affect the structural stress assessment (Fig. 3). Material candidates included structural steel and aluminum alloy A6061. For meshing, the model was discretized using a 5 mm element size, with an average mesh quality exceeding 0.8, thereby ensuring the convergence and accuracy of the results. To accurately simulate operational conditions, link interfaces were defined using frictional contact with a coefficient of friction (μ) of 0.2. The fixed base was defined as a fixed support (Fig. 4), and the degrees of freedom (DOF) of the mechanism were constrained to restrict Z-axis displacement, Y-axis rotation, and X-axis displacement (Fig. 5). A gravitational load corresponding to a mass of 10 kg was applied at the interface between the mechanism link and a constraint block to simulate the pressure exerted by the user's lower limb (Fig. 6).

2.3 Experimental validation of FEA model

To verify the accuracy and reliability of the FEA model, a physical load-bearing experiment was conducted on the CPM device prior to the optimization analysis. The device was configured

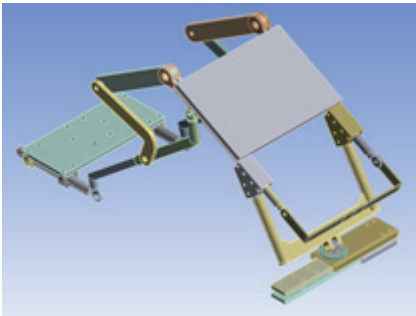


Fig. 3. (Color online) ANSYS model of CPM device.

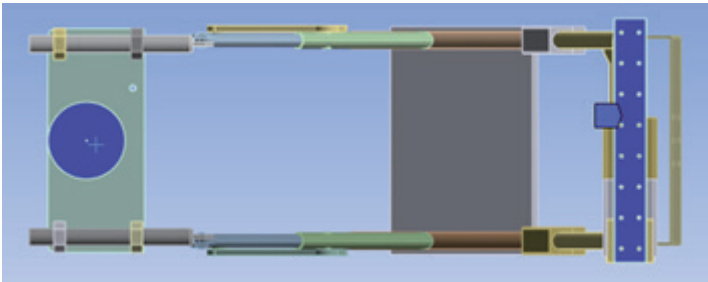


Fig. 4. (Color online) Bottom view of CPM device. The blue region indicates the fixed support boundary condition.

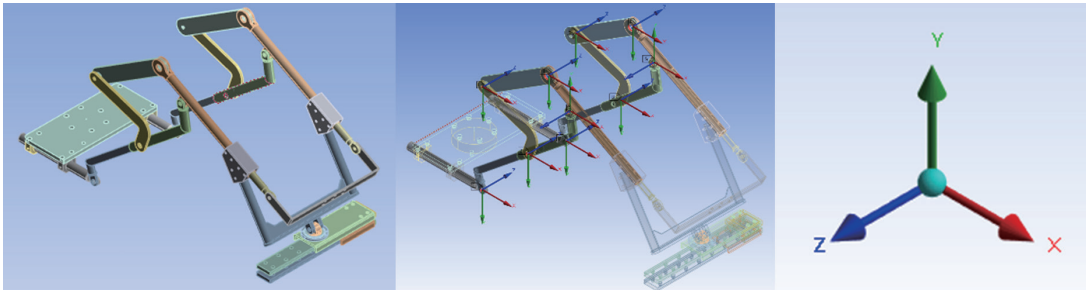


Fig. 5. (Color online) Setup of contact and constraint conditions.

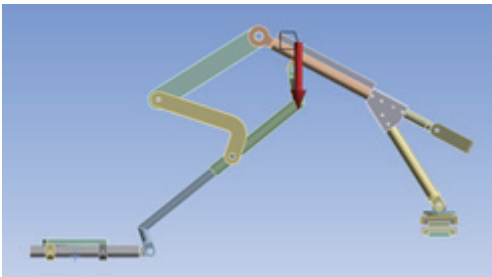


Fig. 6. (Color online) Application point of applied load (indicated by red arrow).

with a fixed-support boundary condition to replicate the constraints established in the numerical model. Loads of varying weights were sequentially applied to predefined points (Fig. 7). The vertical displacement at the designated measurement point was recorded using a displacement transducer (KYOWA DTH-A-20) (Fig. 8) connected to a sensor interface (KYOWA PCD-300B) (Fig. 7). The measurement was repeated three times to ensure data consistency, and the average was recorded. Finally, the measured experimental data were compared with the corresponding FEA predictions under identical conditions, and the percentage error was calculated to evaluate the reliability of the numerical model and its suitability for subsequent Taguchi optimization analysis.

2.4 Taguchi method

The design parameters, referred to as control factors, were selected on the basis of preliminary FEA results and their effect on the two conflicting objectives: structural strength and weight reduction. In this study, we used the Taguchi method for experimental design to address this multi-objective optimization problem. The optimization analysis addressed the multi-objective problem by minimizing the following objective function:

$$\text{Min} = F(x) = W_1\sigma + W_2m, \quad (1)$$

where σ represents the maximum equivalent stress, m represents the mass, and W_1 and W_2 are

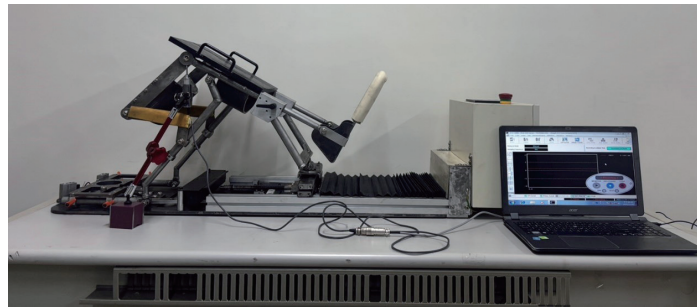


Fig. 7. (Color online) Physical model of CPM device.



Fig. 8. (Color online) Planning and layout of experimental measurement points.

weighting coefficients. In this study, W_1 and W_2 were set to 0.5, giving equal weight to the maximum equivalent stress and mass objectives.

From the preliminary ANSYS stress analysis results obtained under a 50 kg load (Fig. 9), higher stress concentrations were observed in key load-bearing components, namely, members 2, 4, 5, 8, and 11 (Fig. 10). Accordingly, four control factors, each set at three levels, were selected to investigate their combined effects on overall performance.

1. Factor A (material type) assesses the trade-off among material density, stiffness, and ultimate strength.
2. Factor B (cross-sectional design) directly analyzes the relationship between material volume (mass) and structural strength by varying the thickness and utilizing a solid core.
3. Factor C (cross-sectional shape) and factor D (link 11 outer shape) investigate the effects of structural geometry and localized reinforcement on bending stiffness and the efficiency of material distribution.

The specific factors and their levels are detailed in Table 1. The levels were selected to explore the trade-off possibilities between maximizing structural strength and minimizing device weight.

2.5 GRA

The ultimate goal of this research was to simultaneously achieve the maximum structural strength and minimum weight of the CPM device; however, these two quality characteristics are

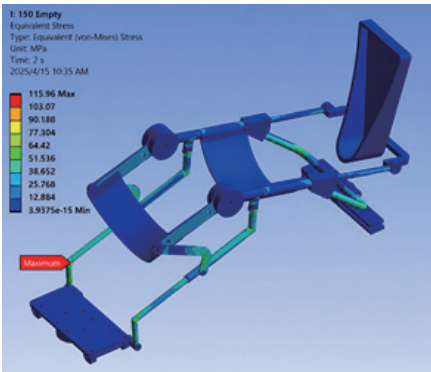


Fig. 9. (Color online) Stress simulation results under a 50 kg load.

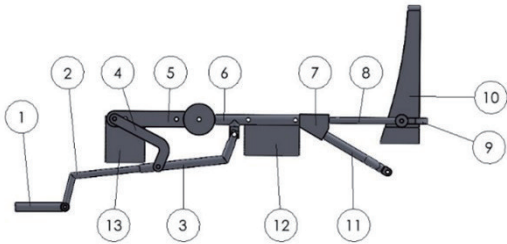


Fig. 10. (Color online) Numbering of mechanism components.

Table 1
Factors and level setting.

Factor	Description	Level 1	Level 2	Level 3
A	Material type	6061-T6	7075-T6	2024-T3
B	Cross-sectional design (Link 2,8)	$T = 1.5\text{ mm}$	$T = 3\text{ mm}$	Solid
C	Cross-sectional shape (Link 4,5)	Rectangle	I-beam	Lattice structure
D	Outer shape (Link 11)	U-shape	Rectangular U-shaped	Rectangular U-shaped with stiffener

inherently conflicting. To integrate these multiple quality objectives into a single evaluation index, GRA was applied to the data generated from the Taguchi experiments. GRA transforms multiple complex performance indices into a single grey relational grade (GRG), thereby facilitating the identification of the optimal set of design parameters. The computational process began with data preprocessing. Owing to the differing units and numerical ranges of the quality characteristics (i.e., maximum equivalent stress and weight), normalization was performed (2) to ensure that both characteristics were evaluated on a comparable scale. Since all quality characteristics in this study were considered “Smaller-is-Better” criteria, where a smaller numerical value indicates better quality, the data were normalized to the range of 0 to 1 using the following equation:

$$x_i^*(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)}. \quad (2)$$

Following normalization, the grey relational coefficient (GRC) was calculated for each experiment using Eq. (3). This coefficient measures the degree of correlation between the normalized data and the ideal reference sequence, which has a value of 1. The GRC was calculated using the following equation:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{0i}(k) + \zeta \Delta_{\max}}. \quad (3)$$

Here, $\Delta_{0i} = |x_0^*(k) - x_i^*(k)|$ is the absolute difference between the reference sequence $x_0^*(k)$ and the normalized sequence, and ζ is the distinguishing coefficient, which was set to 0.5 in this study. Finally, the GRG was determined by calculating the weighted average of the GRCs for each experiment, thereby representing the overall performance of each design combination. The GRG was calculated using the following equation:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k), \quad (4)$$

where γ_i is the GRG for the i -th experiment and n is the number of quality characteristics being analyzed. The final optimal design parameter set was determined by ranking the GRGs.

3. Results and Discussion

3.1 ANSYS simulation and experimental validation

To validate the reliability of the ANSYS model, we compared the numerical simulation results with the physical experimental data. On the basis of the predefined boundary conditions

and load settings, the ANSYS simulation was performed at a flexion angle of 120° to ensure a direct comparison with the experimental results for validation. The simulated displacement was measured using the ANSYS Probe function, which quantified the displacement in the Y-direction at locations corresponding to the physical measurement points. The comparison of the displacement data obtained from the simulation and experiment is presented in Table 2 and Fig. 11.

The comparison results indicated a difference between the simulated and experimental displacement values at the 120° flexion angle, as quantified by the percentage error. This observed error was primarily attributed to the experimental measurement inconsistencies and necessary geometric model simplifications, including the removal of minor features. Despite these discrepancies, the reasonable agreement between the simulated and experimental displacement values indicated that the numerical model adequately reflected the device’s fundamental physical behavior and was suitable for the subsequent optimization analysis. Future work should focus on refining the model structure and enhancing measurement precision to minimize this error. In addition, because the present validation was conducted under static loading conditions, dynamic response and fatigue behavior under repetitive cyclic motion should be further investigated to evaluate the long-term structural reliability of the CPM device.

3.2 Results of Taguchi method and ANSYS analysis

For experimental planning, the Taguchi method was implemented using an L₉ (3⁴) orthogonal array. Subsequently, the experimental runs were subjected to FEA. The FEA boundary and

Table 2
Displacement data comparison: ANSYS simulation versus experimental results.

Factor	Applied load	120°
Simulation		0.13171
Experimental	10 kg	0.121
Deviation		8.8512%

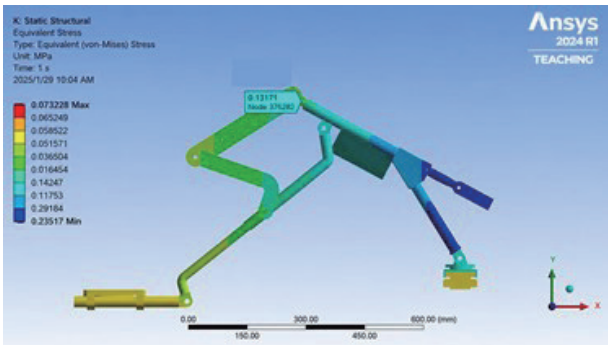


Fig. 11. (Color online) ANSYS simulated displacement.

loading conditions included a 10 kg load, with the corresponding gravitational force applied at the interface between the mechanism link and a constraint block to simulate the pressure exerted by the user's lower limb (Fig. 12). The CPM device was fixed at a 120° flexion angle during the analysis. The stress analysis results for all runs are presented in Table 3 and Fig. 13.

The equivalent stress results, visually represented in Fig. 13, revealed consistent stress concentration regions across all nine experimental runs. Specifically, links 2 and 8 exhibited the highest stresses near the load application point and pin holes owing to the coupled effects of bending and axial loads, whereas links 4 and 5 showed secondary high stress concentrations at geometric discontinuities, and link 11 exhibited stress concentration near the fixed support end. Although the locations of the stress concentrations were consistent, the maximum equivalent stress varied significantly, ranging from 6.1777 MPa (Run No. 4) to 13.84 MPa (Run No. 1) (Table 3). This significant variation confirmed that the stress distribution and peak values were strongly affected by the design factors (cross section and outer shape).

3.3 Results of multi-objective optimization using GRA

GRA was performed using equal weighting of 50% for maximum equivalent stress and 50% for weight. Table 4 presents the *GRG* calculated from the maximum equivalent stress and weight

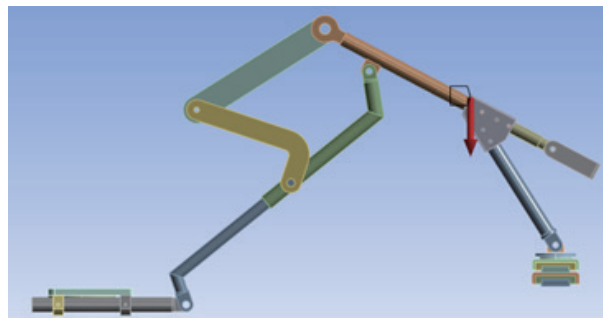


Fig. 12. (Color online) Loading position.

Table 3
Equivalent stress results from ANSYS simulation.

Experiment no.	Maximum equivalent stress (MPa)
1	13.84
2	10.433
3	6.4934
4	6.1777
5	8.4095
6	10.438
7	13.81
8	6.2267
9	8.373

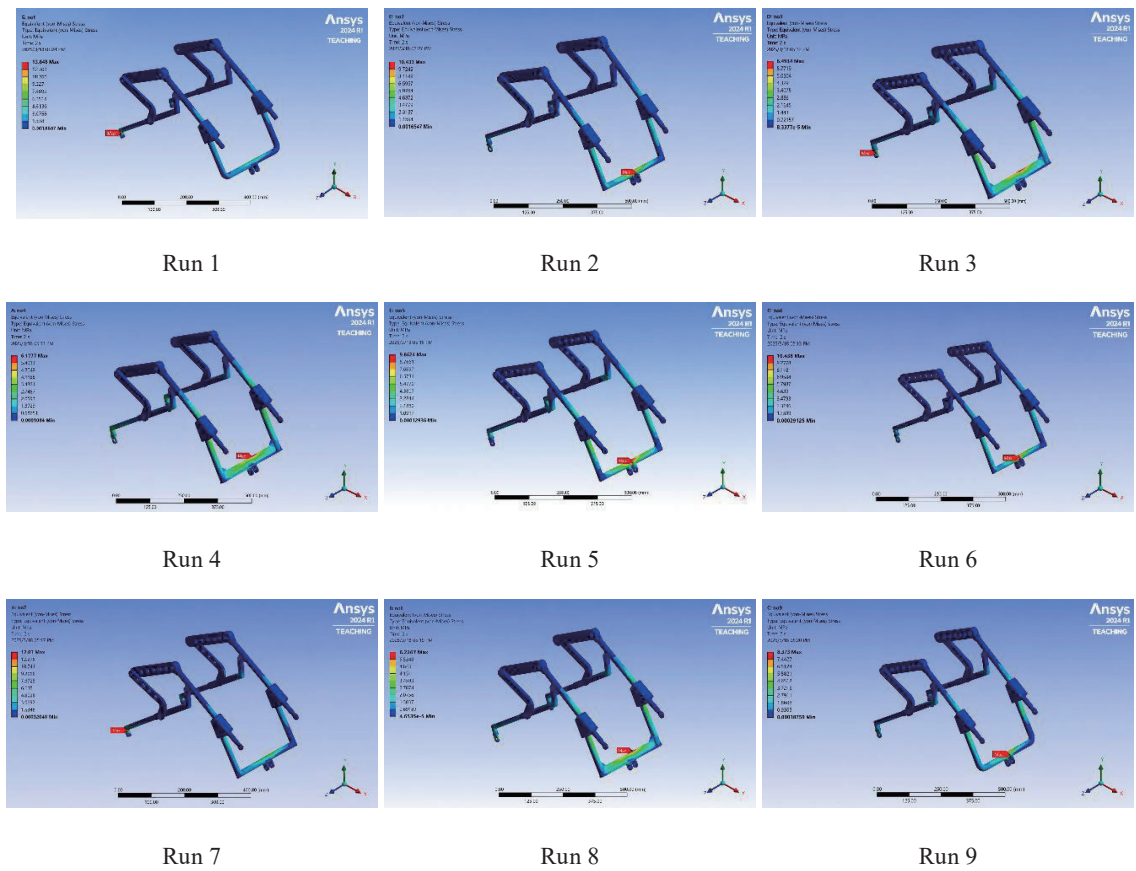


Fig. 13. (Color online) Equivalent stress analysis results from L9 orthogonal array experiments.

Table 4
L9 orthogonal array in 5:5.

Exp	A	B	C	D	Y1	Y2	<i>S/N</i> (1)	<i>S/N</i> (2)	<i>GRG</i>
1	1	1	1	1	13.8400	6.6966	−22.8227	−16.5171	0.5485
2	1	2	2	2	10.4330	6.6189	−20.3682	−16.4157	0.7070
3	1	3	3	3	6.4934	7.0378	−16.2494	−16.9488	0.6422
4	2	1	2	3	6.1777	6.6132	−15.8165	−16.4082	1.0000
5	2	2	3	1	8.4095	6.9012	−18.4954	−16.7784	0.5270
6	2	3	1	2	10.4380	7.1714	−20.3723	−17.1121	0.3840
7	3	1	3	2	13.8100	6.6261	−22.8039	−16.4252	0.6439
8	3	2	1	3	6.2267	6.9222	−15.8852	−16.8049	0.7254
9	3	3	2	1	8.3730	7.0536	−18.4576	−16.9682	0.4780

data obtained from the nine L9 orthogonal array experiments (runs 1 to 9). Run 4 achieved the highest *GRG*, with a value of 1, confirming its optimal overall performance under this balanced weighting scenario. Figure 14 shows the factor response graph, which visually displays the average *GRG* derived from Table 4 for each level of the four control factors.

The influence ranking of the control factors was determined to be $D > B > C > A$ (Table 5). Factor D (link 11 outer shape) showed the greatest effect (0.8141), followed by factors B (0.6881)

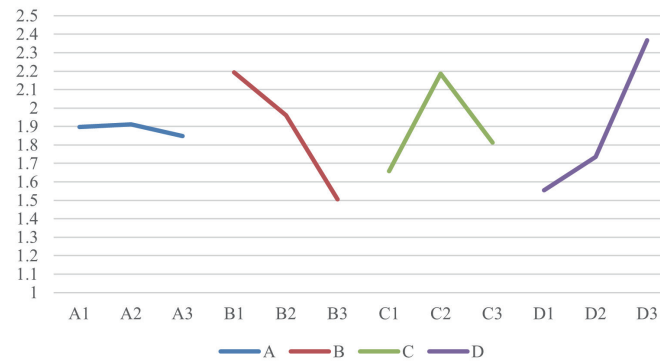


Fig. 14. (Color online) Factor response graph.

Table 5
Main effect plot table.

Factor	A	B	C	D
Level 1	1.897685116	2.19233569	1.657913578	1.553501766
Level 2	1.911013416	1.959490102	2.185080596	1.734927936
Level 3	1.847346204	1.504218943	1.813050561	2.367615033
Effect	0.063667212	0.688116747	0.527167018	0.814113268
Rank	4	2	3	1

and C (0.5272), with factor A exhibiting the least influence (0.0637). On the basis of the highest average *GRG* (Fig. 14), the optimal design parameter combination was determined to be A2B1C2D3. This combination provided the best balance between structural strength and weight reduction for the CPM device under the $W_1 = 0.5$ and $W_2 = 0.5$ weighting scenario.

3.4 Analysis of factor interaction effects

This interaction analysis was based on the results obtained under the weighting scenario of 50% maximum equivalent stress and 50% weight. The analysis specifically examined the factors with the greatest effect: factors B, C, and D. As demonstrated by the data in Tables 6–8 and the corresponding plots in Figs. 15–17, the different slopes and intersecting lines indicated strong interaction effects among these factors. These plots were generated by calculating the average *GRG* for each two-factor level combination from the primary L_9 experimental results. Notably, the analysis identified a particularly strong $B \times C$ interaction (Table 6, Fig. 15). This interaction was indicated by the pronounced intersection between the factor lines, suggesting that the optimal level for factor B depended strongly on the level chosen for factor C, and vice versa. This strong interaction highlighted the necessity of considering the simultaneous effects of factors B (cross-sectional design) and C (cross-sectional shape) during the optimization process. Therefore, future design efforts should consider these interacting parameters together to ensure that the final parameter combination achieves the best possible overall performance.

Table 6
Interaction effect values for Factors B × C.

	B1	B2	B3
C1	0.548463805	0.725440061	0.384009713
C2	1	0.707046338	0.478034258
C3	0.643871885	0.527003703	0.642174973

Table 7
Interaction effect values for Factors B × D.

	B1	B2	B3
D1	0.548463805	0.527003703	0.478034258
D2	0.643871885	0.707046338	0.384009713
D3	1	0.725440061	0.642174973

Table 8
Interaction effect values for Factors C × D.

	C1	C2	C3
D1	0.548463805	0.478034258	0.527003703
D2	0.384009713	0.707046338	0.643871885
D3	0.725440061	1	0.642174973

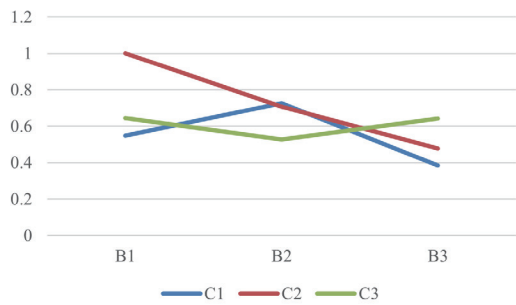


Fig. 15. (Color online) Interaction plot of factors B × C.

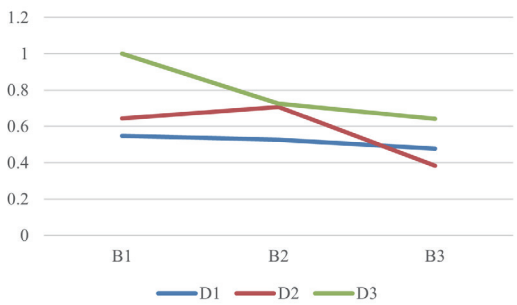


Fig. 16. (Color online) Interaction plot of factors B × D.

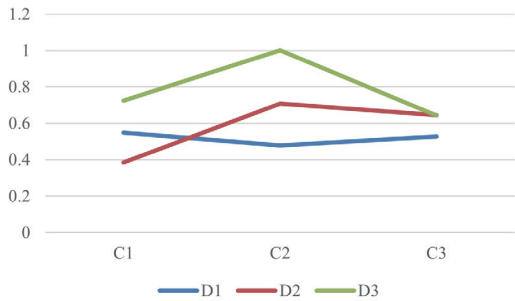


Fig. 17. (Color online) Interaction plot of factors C × D.

4. Conclusions

In this study, we developed and optimized a novel CPM device. The numerical model was experimentally validated through sensor-based displacement measurements of the physical device. The systematic optimization framework, combining sensing-based experimental validation, FEA, and the Taguchi–GRA method, achieved a multi-objective balance between structural integrity and weight reduction. The quantified results and structural implications are as follows.

1. Optimal design and influence: The optimization analysis identified the optimal parameter combination as A2B1C2D3, confirmed by the highest *GRG*. The factor ranking by influence magnitude was determined to be $D > B > C > A$.
2. Performance gains: The final optimized design (Run A2B1C2D3) achieved a 55.5% reduction in maximum equivalent stress compared with the baseline design, with the resulting maximum equivalent stress being significantly lower than the material's yield strength. This structural improvement was accompanied by a 15% reduction in weight.
3. Structural interaction: A strong $B \times C$ interaction effect was identified, highlighting the necessity of considering the combined effects of cross-sectional design and shape in structural optimization.
4. Future applicability: The established optimization process provides a systematic reference for the structural design of rehabilitation devices and may be applicable to improving the structural performance of similar medical aids or humanoid robot structures.

In the present study, we primarily focused on the structural analysis and optimization of the CPM device under static loading conditions. Since CPM devices operate under repetitive cyclic motion during rehabilitation, in future work, we will investigate the dynamic response and fatigue behavior of the device through dynamic structural analysis, fatigue simulation, and cyclic loading experiments to further evaluate its long-term safety and reliability. In addition, patient–device interaction, biomechanical and ergonomic assessments, usability studies, and pilot clinical evaluations will be conducted to further assess the clinical applicability and practical effectiveness of the device. In future studies, we will also integrate kinematic and control-system parameters, including motor speed, torque, and feedback characteristics, with the structural model to evaluate their effects on the dynamic behavior and overall performance of the CPM device.

Acknowledgments

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