SIN-CHN SCIENTIFIC PRESS PTE.LTD.

Molecular & Cellular Biomechanics 2025, 22(2), 984.
https://doi.org/10.62617/mcb984

Article

Application of biomechanics in graphic design and ergonomic optimization

Wei Wei

School of Fine Arts, Xinxiang University, Xinxiang 453000, Henan, China; weiwei1101@xxu.edu.cn

CITATION

Wei W. Application of biomechanics in graphic design and ergonomic optimization. Molecular & Cellular Biomechanics. 2025; 22(2): 984. https://doi.org/10.62617/mcb984

ARTICLE INFO

Received: 2 December 2024
Accepted: 16 December 2024
Available online: 21 January 2025

Abstract: For patients recovering from spinal diseases, ordinary seats often lack support and correction functions, which can easily lead to problems such as spinal curvature and lumbar disc herniation. The study uses MediaPipe to recognize postures and perform 3D graphics modeling, combined with finite element analysis to simulate the coordinated work of the patient's muscles, bones, and joints, and optimize the design of ergonomic orthosis. First, MediaPipe Pose is used for posture recognition to capture the key point coordinates of the spine and joint positions and obtain dynamic data of the patient's sitting posture. Next, a 3D model of the patient's skeleton and spine is built, and the bone structure is generated based on the posture data and refined with ZBrush. Then, a finite element analysis is performed using ANSYS Workbench, and the stress distribution of the spine under the patient's weight and different sitting pressures is simulated. The orthopedic seat's geometry and support area distribution are optimized, and adjustment functions are added to improve adaptability. The data results show that the MSE (Mean Square Error) of the optimized spinal curve deviation is only 0.0009; the maximum stress of the intervertebral disc is reduced from 56.1 MPa to 42.4 MPa; the area of the high-stress area is reduced to 12.4cm²; the stress uniformity is improved by 28.1%; the local pressure is reduced by 24.6%. The designed method can significantly reduce the patient's spinal deviation rate, relieve seat pressure, and have a good rehabilitation auxiliary effect.

Keywords: biomechanics and ergonomics; graphic design; spinal rehabilitation; pose recognition; finite element analysis

1. Introduction

With the rapid development of modern society, the long-term sedentary work mode has led to a significant increase in the incidence of spinal health problems. Long-term computer operation in the office environment and unreasonable seat design is prone to cause diseases such as lumbar disc herniation and spinal curvature [1–3], which seriously affect the quality of life of patients and bring heavy social and economic burdens [4,5]. Existing studies have shown [6,7] that traditional seats are unable to meet the needs of patients due to the lack of adequate spinal support [8,9] and personalized correction functions [10,11], which delays the rehabilitation process. Posture adjustment and correction are key links in rehabilitating spinal diseases [12,13], but the existing orthopedic seat design has failed to solve this problem effectively. Based on the biomechanical needs of patients, designing a seat with both support and correction functions has become a hot topic that needs to be solved urgently.

Some researchers have begun to try to improve the design of orthopedic seats through different research approaches to make it more ergonomic. Wang et al. [14] proposed a seat design that combined Spiking neural network and pressure sensing technology, using seat surface pressure sensors to monitor sitting posture in real-time and automatically adjust the seat's tilt angle and height through a feedback mechanism. De Mare Lieke et al. [15] developed a seat that can automatically adjust support according to individual needs through dynamic analysis of human sitting posture and combined with the use of flexible materials. Combining the vibration dose value and the maximum transient vibration value, Teron et al. [16] developed a three-layer ANN (Artificial Neural Network) model to precisely adjust the seat parameters of bus passengers and improve comfort. In response to the shortcomings of existing flat armchairs, Nooraziah et al. [17] used a combination of neural networks and MLR (Multiple Linear Regression) for predictive analysis in 2024 and successfully developed a new ergonomic chair. Although such research [18,19] has made some progress, most solutions rely on static sitting data and fail to fully consider the human body's posture changes and individual differences in an active state [20,21]. Researchers such as Math [22] and Ahmed [23] tried to optimize seat design by combining traditional mechanical models, but their methods still have certain limitations and cannot meet the needs of different patients in different situations [24]. Overall, existing research has not effectively solved the problem of optimizing the design of rehabilitation patient seats through dynamic adaptability and personalized adjustment.

Recently, some studies have combined advanced technologies such as 3D modeling and biomechanical analysis to try to improve the intelligence and personalization of orthopedic seat design. Combining 3D human body scanning and finite element analysis, Igor et al. [25] precisely modeled the patient's bones, muscles, and joints and simulated the impact of the seat on the spine under different sitting postures, thereby optimizing the seat shape and support point distribution. In 2021, Mark et al. [26] proposed a posture recognition method based on virtual reality (VR) technology, combined with finite element analysis to adjust the hardness and tilt angle of the seat in real-time to adapt to different human needs. Sidrah [27] and Lepora [28] and other researchers applied convolutional neural networks (CNN) to posture recognition and seat adjustment processes, and used algorithms to monitor and provide feedback on the patient's dynamic sitting posture in real-time. Existing studies have shown that 3D modeling [29,30] and biomechanical simulation [31–33] can provide more accurate data support for seat design, but there are still problems of insufficient adaptation to individual differences [34–36] and lack of adjustment ability during dynamic rehabilitation [37,38].

In recent years, the application of biomechanics in graphic design and ergonomic optimization has made significant progress, especially in the areas of seat design and spinal health. Dong et al. [39] studied the impact of sitting posture on spinal vibration behavior, revealing the role of foot and calf positioning on spinal health, and emphasizing the synergistic effects of different body parts on spinal load. Habegger et al. [40] proposed a design for a high-static, low-dynamic seat cushion, which reduces friction and optimizes pressure distribution, thus improving comfort during prolonged sitting. Kyeong [41] analyzed the impact of chair tilt functions on users' biomechanical signals and comfort, providing a quantitative relationship between seat design and ergonomic signals. Singh et al. [42] applied a hybrid artificial neural network and genetic algorithm approach to analyze real-time vibration exposure during mini combine harvester operations, exploring the impact of vibration on the operator's spine. Alshehri et al. [43] examined hip and spine coordination in individuals with acute low back pain during unstable sitting, investigating how seat design can mitigate the negative effects of poor coordination. Wang et al. [44] explored the influence of seat back angle on seat design for autonomous vehicles, offering new insights into seat design for highly automated vehicles. Based on the integration of MediaPipe posture recognition and finite element analysis, this paper proposes an innovative spinal correction seat design, aimed at optimizing posture adjustments and pressure distribution for patients in rehabilitation, with high practical application value and socio-economic impact. Through precise spinal curve optimization and stress distribution simulation, this design effectively reduces spinal deviation and intervertebral disc pressure, decreases high-pressure areas, and improves the comfort and adaptability of the seat. It provides a new supportive solution for rehabilitation treatment, fills the gap in current research on personalized spinal correction seats, and offers theoretical and practical support for future seat design and rehabilitation technology applications.

This study applies a new design scheme that integrates MediaPipe posture recognition, 3D modeling, and finite element analysis to optimize the design effect of spinal disease rehabilitation seats. First, a high-resolution RGB (Red, Green, Blue) camera and MediaPipe Pose model are used to collect and process patient sitting images. The data is smoothed by Kalman filtering; the coordinate system is standardized; outliers are cleaned to ensure data continuity and accuracy. Based on the cleaned data, an elastic body mechanics model considering the flexibility of the intervertebral disc is established through three-dimensional modeling and finite element analysis; the interaction force between the spine and the intervertebral disc is simulated; a detailed three-dimensional model of the spine and muscles is constructed. After the model is constructed, finite element analysis is performed using ANSYS; material properties are defined, and boundary conditions and loading modes are set; the stress distribution of the spine in different sitting postures is analyzed, and the pressure points in the lumbar spine and sacral area are focused on. Finally, based on the stress distribution analysis results, SolidWorks is used to optimize the geometric shape of the orthopedic seat, including adjusting the backrest curvature, increasing the local support thickness, applying the spinal curve fine-tuning function, optimizing the seat cushion design, and selecting suitable surface materials. At the same time, modular adjustment functions are added, including personalized adjustment of the backrest angle, seat cushion height, and lumbar support force, to improve the adaptability and comfort of the seat. The main contributions of this paper are:

Comprehensive use of high-resolution RGB cameras and MediaPipe Pose models combined with Kalman filtering technology can achieve accurate sitting posture data collection and processing.

For the first time, the elastic body mechanics and contact mechanics models are applied to the simulation analysis of the intervertebral disc and spine, and the stress distribution of the spine under different sitting postures is accurately evaluated through three-dimensional modeling and finite element analysis.

A modular orthopedic seat based on stress distribution optimization is applied, considering the optimization of pressure points in the lumbar and sacral areas, significantly improving the adaptability and comfort of the seat.

2. Ergonomic orthopedic seat design based on graphics optimization

2.1. Posture recognition and data acquisition

MediaPipe is an open-source, cross-platform framework designed for efficient real-time computer vision tasks. The framework uses Convolutional Neural Networks (CNNs) to extract key points and features from images, combined with a graph-based pipeline structure that allows multiple data flows and models to be processed in parallel. The core modules of MediaPipe include model inference, image preprocessing, post-processing, and result output. In the task of posture recognition, deep neural networks are used to predict the positions of the human body's key points in real time. During processing, image data is first standardized and adjusted by the preprocessing module, then passed through the neural network for inference, outputting coordinate data. To achieve efficient real-time processing, MediaPipe introduces a graph computing model, dividing different processing steps into multiple nodes, each responsible for a specific task. This modular and parallel approach optimizes computational efficiency. Additionally, MediaPipe uses efficient memory management and hardware acceleration techniques to ensure performance across different devices. With this optimized design, MediaPipe provides high-precision and high-efficiency posture recognition, widely used in human motion capture, posture analysis, and other fields.

In this study, the MediaPipe Pose model is used to perform posture recognition of patients' sitting positions. This model can accurately extract the three-dimensional coordinates of the spine, pelvis, and major joints, providing high-resolution dynamic posture data. To ensure the accuracy and reliability of the data, several optimization measures are taken. First, a high-resolution RGB camera is used to capture images, and the collected posture data is smoothed using a Kalman filter, reducing coordinate fluctuations caused by dynamic movements or external environmental factors. To eliminate the influence of individual differences, all sitting posture data is standardized and normalized relative to the center of the pelvis using a unified coordinate system, enhancing the consistency and comparability of the data. Furthermore, during the data cleaning phase, outliers are removed to ensure the continuity of the data. The overall sitting posture visualization extracted by MediaPipe Pose is shown in **Figure 1**.

Figure 1. Sitting posture extraction based on MediaPipe pose.

Since the initial posture data often contains noise and inconsistency, data cleaning is used to remove outliers and ensure data continuity. The collected data is converted into a standardized file format to facilitate the subsequent 3D modeling and finite element analysis process. In the analysis of the sitting posture problem, the critical points of the spine are fitted to evaluate their deviation from the standard anatomical curve, thereby identifying possible deviation and curvature problems of the spine. At the same time, by analyzing the angle changes between the key points, potential patient posture problems are further determined, including spinal anteversion and posterior tilt, as shown in **Figure 2**.

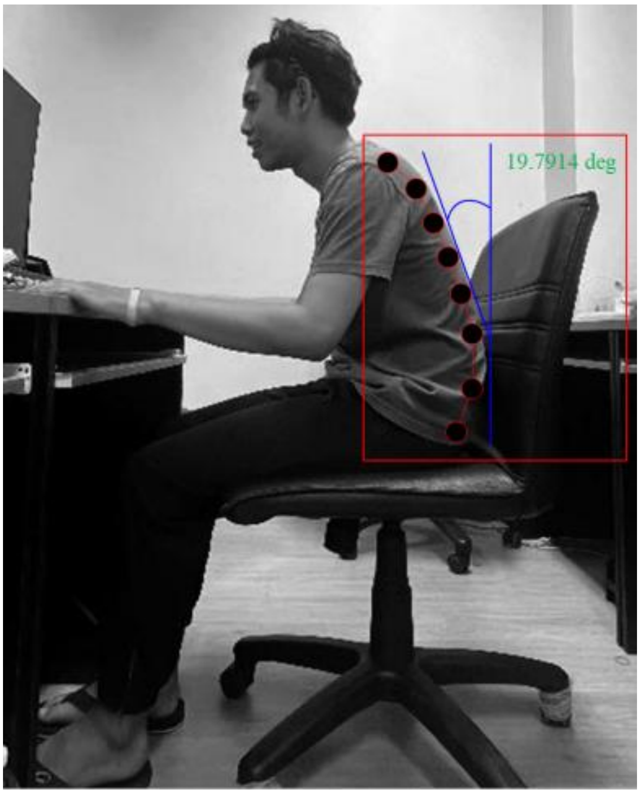

Figure 2. Analysis of spinal deviation.

2.2. Graphical modeling and mechanical analysis

Considering the flexible characteristics of the intervertebral disc, the study uses an elastic body mechanics model to simulate it. By applying the strain energy function, the stress-strain relationship of the intervertebral disc is expressed by the following generalized Hooke's law:

$$E\sigma = \sigma(x) = \mathbb{C}: \varepsilon(x) \tag{1}$$

$\sigma(x)$ is the stress tensor of the intervertebral disc material at position x; $\mathbb{C}$ is the elastic tensor of the intervertebral disc; $\varepsilon(x)$ is the strain tensor at this position. The strain tensor ε is obtained by the following strain-displacement formula:

$$\varepsilon = \frac{1}{2}(\nabla u + (\nabla u)^T) \tag{2}$$

Among them, u represents the displacement field; ∇u is the displacement gradient; $(\nabla u)^T$ is its transpose. The derivative of the displacement field calculates the strain tensor and reflects the deformation inside the intervertebral disc. The anisotropy of the elastic material is realized by the elastic tensor $\mathbb{C}$ in the stress-strain relationship, which varies in different areas of the intervertebral disc. Considering the interaction between the intervertebral disc and the spinal bones, the contact force between the spine and the intervertebral disc is described by the contact mechanics' model:

$$F_{contact}(x) = \int_{\Gamma} k(x)(d(x) - d_0)d\Gamma \quad (3)$$

$F_{contact}$ is the resultant force in the contact area between the intervertebral disc and the spinal bones; Γ is the contact surface; $k(x)$ is the contact stiffness coefficient, which represents the contact surface's stiffness change; $d(x)$ is the local deformation of the contact surface at position x; d_0 is the initial contact distance. The nonlinear characteristics of the contact force model are reflected in the change of the contact stiffness $k(x)$ with the compression deformation. The contact stiffness is zero in the non-contact state and increases with the compression increase in the contact state. A preliminary bone model is constructed after using MediaPipe Pose to obtain the coordinate data of the critical points of the spine and joints. The critical point data is imported into the 3D modeling software to generate a rough framework of the spine, and the reverse modeling technology is used to refine the bone structure further. By scanning the existing anatomical data and combining the patient's individual posture data, a three-dimensional model that conforms to the actual physiological structure is created: starting from the basic morphology of the spine, based on the posture data, the bone generation tool in the CAD (Computer-Aided Design) software is used to refine the geometry of each vertebra, as shown in **Figure 3**.

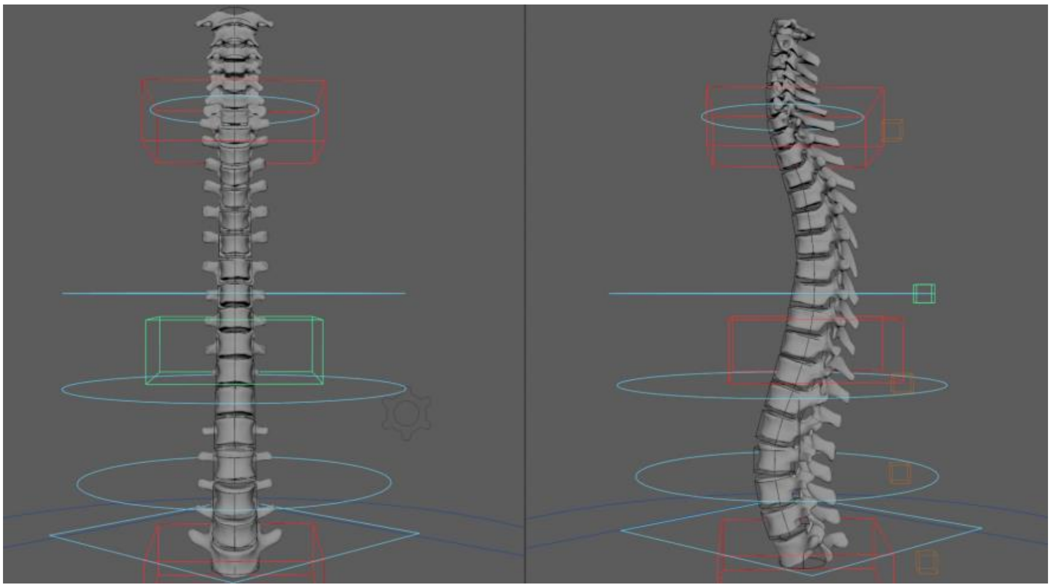

Figure 3. 3D modeling of the spinal cone morphology.

ZBrush is used for surface refinement to improve the model's detail accuracy and surface smoothness. The bone surface is refined on the basis of maintaining the original morphology, removing any irregular shapes and geometric defects in the model, and presenting details such as intervertebral discs, spinal protrusions, and joint spaces, as shown in **Figure 4**.

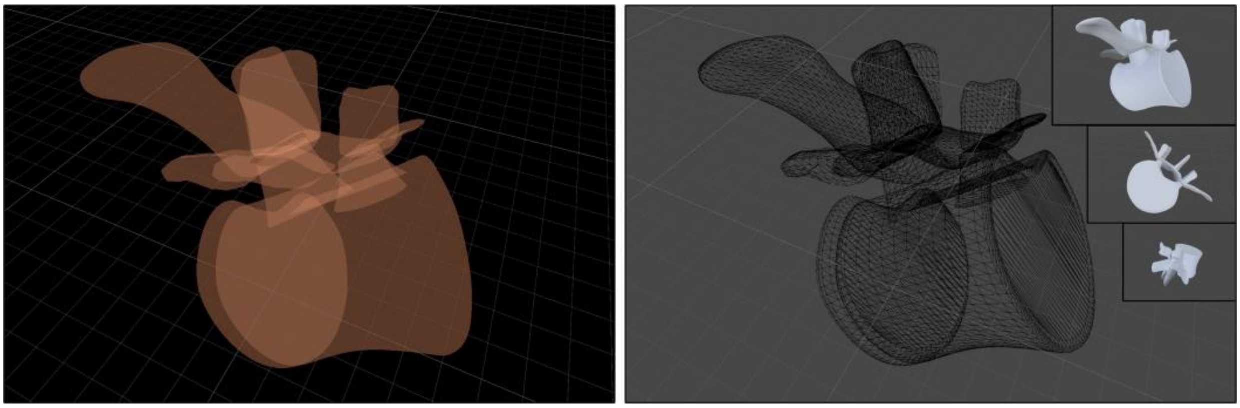

Figure 4. Refinement of the skeletal spinal cone morphology based on ZBrush.

The critical point data and 3D modeling results collected based on MediaPipe are imported into ANSYS. The geometric model includes the spine, intervertebral disc, pelvis, and surrounding soft tissues. The contact relationship between the bone and the intervertebral disc is defined as surface-to-surface contact, and the initial gap of the contact surface is $\Delta_0 = 0.5\text{mm}$. The model is meshed with high quality using an adaptive meshing strategy. The critical stress area of the spine (interface between the annulus fibrosus and the vertebra) is locally meshed; the unit size is controlled at h ≈ 0.5mm ; the mesh quality evaluation index is: $\text{Skewness} = \frac{\text{V}-\text{V}_{\text{ideal}}}{\text{V}_{\text{ideal}}} < 0.2, \text{Aspect Ratio} < 3.5$. Among them, V is the actual mesh unit volume; V_{ideal} is the ideal unit volume; the final total number of mesh units is 2.6×10^6.

Material parameters are assigned according to the biomechanical properties of the spine, where the vertebrae are isotropic linear elastic materials, defined as: $\text{E}_{\text{bone}} = 12\text{GPa}, \nu_{\text{bone}} = 0.3$. The annulus fibrosus of the intervertebral disc is a biaxial tensile model, and the elastic modulus is: $\text{E}_{\text{fib}} = 4\text{MPa}, \nu_{\text{fib}} = 0.45$. The nucleus pulposus of the intervertebral disc is a quasi-liquid material, defined as: $\text{E}_{\text{nucleus}} = 1\text{MPa}, \nu_{\text{nucleus}} = 0.49$. When simulating the patient's sitting posture, the bottom of the pelvis is fixed to limit the degree of freedom. The constraint conditions are:

$$u_x = u_y = u_z = 0, \forall r \in \Omega_{pelvis} \tag{4}$$

Here, Ω_{pelvis} is the pelvic bottom area. At the same time, symmetric constraints are set for both hip joints to reduce non-physical deformation. Static and dynamic loads are applied according to the patient's weight and sitting posture characteristics:

$$\begin{cases} F_z = \dfrac{W}{A_{pelvis}}, A_{pelvis} = \pi R^2 \\ p(x, y, t) = p_0(1 + \alpha sin(2\pi f t)) \end{cases} \tag{5}$$

Among them, R is the equivalent radius of the pelvic contact area; p_0 is the average load density; α is the amplitude coefficient; f is the dynamic frequency, and $\text{f} = 0.5\text{Hz}$ is taken. The stress concentration area is calculated using the Von Mises stress formula:

$$\sigma_{VM} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \tag{6}$$

Here, σ_1, σ_2, and σ_3 are the principal stresses. At the same time, 3D simulation of muscles and intervertebral discs is further added. According to the patient's individual data, the geometric structure of the back muscles is generated by the modeling software. A modeling method based on muscle mechanics is used to simulate the distribution of muscles and their relationship with the spine and bones. The stress-strain relationship of muscle fibers represents the mechanical properties of muscles. The starting and ending points of each muscle, the direction of the muscle fibers, and the tension distribution of the muscles are set, and the contraction force of the muscles is described by the Lagrangian mechanics model, as shown in **Figure 5**.

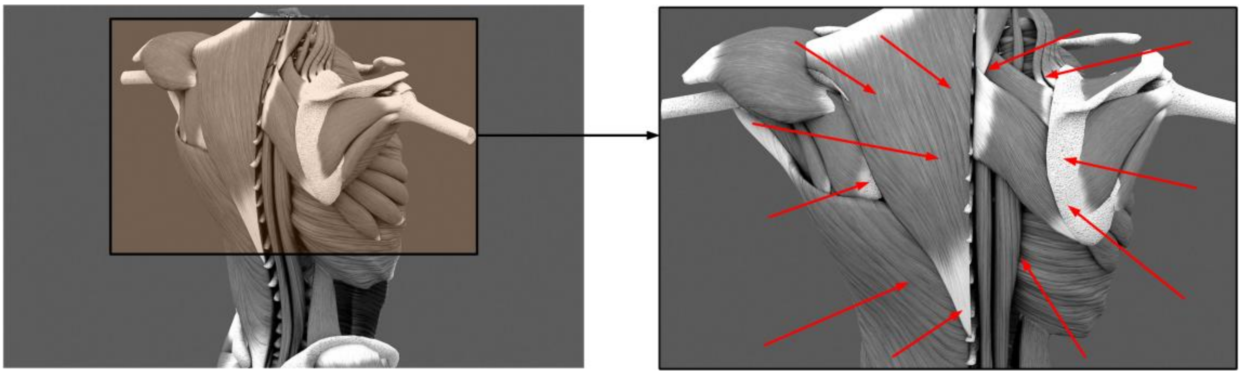

Figure 5. Geometric modeling of back muscles.

Assuming that the mechanical behavior of the back obeys the Hill model, its expression is:

$$F_m = F_{max} \times (\frac{L}{L_{opt}})^n (1 - \frac{L}{L_{max}}) \tag{7}$$

Among them, F_m represents the force generated by the muscle; F_{max} is the maximum force generated by the muscle; L is the current length of the muscle; L_{opt} is the optimal working length of the muscle; L_{max} is the maximum stretch length of the muscle; n is a parameter, which is set to 2.5 in the study.

2.3. Orthopedic seat design and optimization

The finite element analysis based on ANSYS Workbench provides stress distribution data for optimizing the seat support area. The study further identifies the stress concentration areas of the spine under different sitting postures and weights, focusing on the pressure points in the lumbar spine and sacrum areas. The analysis results show that the stress distribution of traditional seats in these areas is uneven, and there are obvious high-pressure areas. Such high-pressure points are an essential factor that worsens patients' spinal problems. The visualization is shown in **Figure 6**.

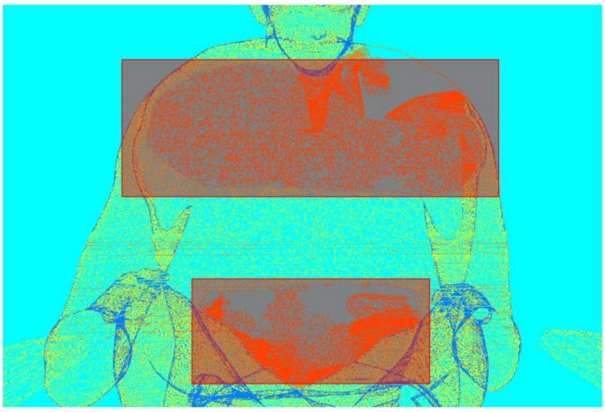

Figure 6. Simulation of the high-pressure area on the patient's back.

Then, SolidWorks is used to optimize the seat geometry based on the simulated stress distribution data. In the seat back area, the curvature and shape of the backrest are adjusted to ensure that it can provide more uniform support in the lumbar spine. After the adjustment, the backrest is thickened in some areas to enhance the support strength for the waist. At the same time, a fine-tuning function that conforms to the natural curve of the human spine is applied, so that the seat can automatically adapt to the patient's sitting posture. The optimization of the seat cushion part is to add an adjustable support plate to meet the needs of different patients, and the contact area of the buttocks and thighs adopts an ergonomic wave design to achieve a better pressure distribution effect. The seat surface material uses high-elastic polymer and memory foam material to ensure that local pressure can be effectively relieved when sitting for a long time. High-elastic polymer is used in the seat's key support areas, including the lumbar spine and back support modules. The material can provide sufficient support when the patient sits down and quickly recovers to its original state when standing up to avoid support deformation. The memory foam material is used on the contact surface between the seat cushion and the backrest, and its shape is dynamically adjusted according to the patient's weight and sitting posture to reduce the discomfort caused by long-term use. The seat's overall design and adjustment process are shown in **Figure 7**.

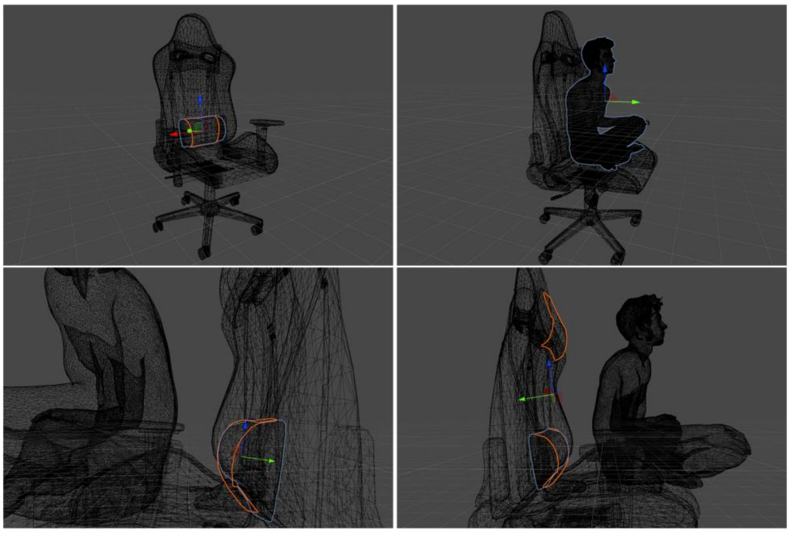

Figure 7. Orthopedic seat design and optimization process.

At the same time, modular adjustment is applied in the design to personalize the backrest angle, seat cushion height, and lumbar support. The backrest angle can be adjusted from 15 to 30 degrees to adapt to different spinal curvatures and patients' sitting posture requirements. The seat cushion height and front and back position can be fine-tuned according to the patient's leg length and sitting depth to ensure that the knees maintain a suitable angle with the ground to avoid poor blood circulation in the lower limbs due to long-term sitting. The lumbar support module adopts an adjustable air pressure design. After collecting patient imaging data every day, the support hardness of the lumbar area is adjusted to relieve discomfort caused by spinal deformation and excessive pressure.

3. Design evaluation

3.1. Spinal curve deviation rate

The design of this experiment aims to assess the impact of ergonomically optimized orthotic seats based on biomechanical principles on patients recovering from spinal diseases, particularly in terms of spinal correction, stress distribution optimization, pressure relief, and rehabilitation support. The participants are patients aged between 18 and 65 who are in the recovery phase from various spinal disorders, including lumbar disc herniation, scoliosis, and age-related spinal degeneration. Inclusion criteria for participants are as follows: 1) patients diagnosed with spinal diseases and in the recovery phase, who have not undergone other orthopedic treatments; 2) participants in good physical health, capable of participating in sitting posture simulations and using the seat; 3) no severe cognitive impairments or other health issues that could affect participation. Exclusion criteria include: 1) individuals with active spinal tumors or infections; 2) patients unable to maintain a stable sitting posture during the experiment; 3) individuals with severe other orthopedic conditions or mental disorders that may interfere with the experimental results.

A randomized controlled trial (RCT) design is employed. All participants will first undergo baseline assessments, including spinal curve deviation rate, electromyography (sEMG) data collection, and pressure distribution testing. After adequate rest and acclimatization, participants will undergo a 28-day seating test. During the experiment, MediaPipe Pose technology will be used to monitor each participant's sitting posture in real time, collecting posture data from key points along the spine and constructing a 3D skeletal model based on this data. Finite element analysis (FEA) will be performed to simulate the stress distribution in the spine under different sitting postures, focusing on the stress concentration areas of the intervertebral discs and spinal bones. The experiment will also measure pressure changes in the lumbar and sacral regions under different sitting postures to assess the effectiveness of the optimized seat in alleviating localized pressure.

Throughout the experiment, all participants will use the seat in a standardized environment and undergo regular posture assessments and physiological feedback monitoring. The experiment controls for variables in participants' sitting postures, including normal sitting, forward-leaning sitting, and slouched sitting, to comprehensively analyze the seat's performance under different conditions. The orthotic seat used is a customized design based on biomechanical analysis, incorporating adjustable support areas and a flexible pressure distribution system to maximize comfort and promote spinal health recovery.

Data collection includes baseline and post-experiment physiological data (such as spinal curve deviation, stress distribution, and localized pressure) as well as muscle activity data monitored through sEMG. In addition, all participants will complete a satisfaction survey at the end of the experiment, evaluating support, stability, comfort, and other aspects. The experimental data will be processed using statistical analysis to assess the effectiveness of the optimized design in promoting patient recovery, particularly in reducing spinal deviation, alleviating localized pressure, improving muscle fatigue, and enhancing comfort.

MediaPipe Pose is used to extract the coordinate data of the key points of the patient's spine before and after sitting. The curve change trend is calculated by comparing the deviation between the key points and the standard anatomical curve position. The change in the deviation rate is quantitatively analyzed by piecewise linear fitting to evaluate the effect of the seat on correcting the spinal curve. The results are shown in **Figure 8**.

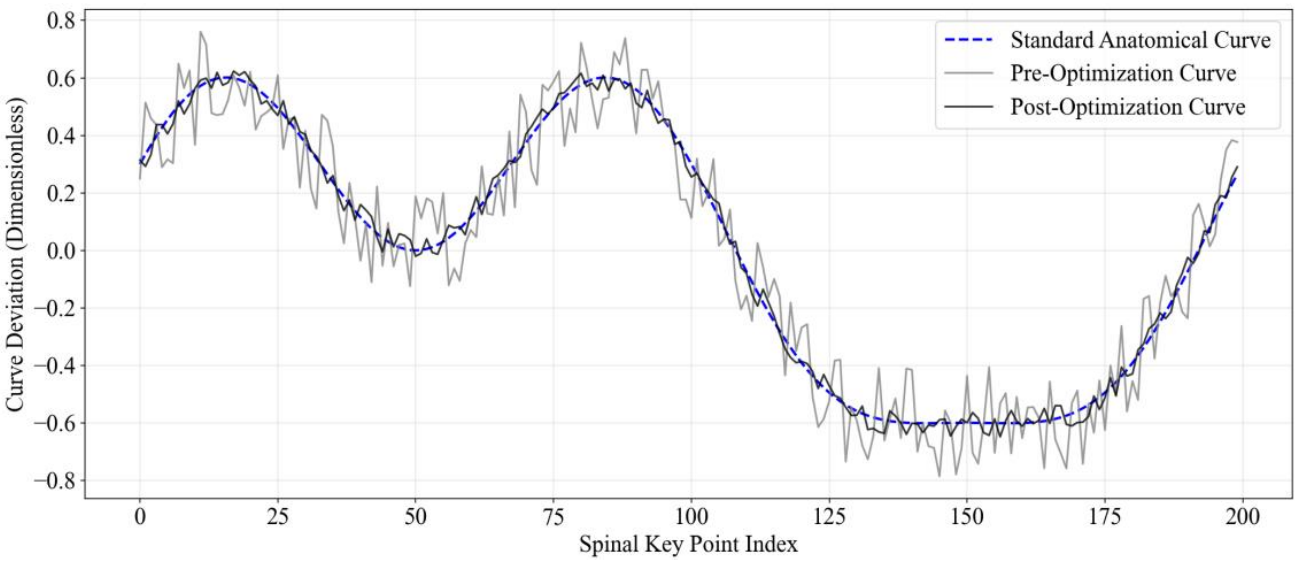

Figure 8. Deviation of the spinal curve.

Through standardization, the unit difference caused by factors such as different body shapes and spinal lengths is eliminated using dimensionless deviation values. The horizontal axis of **Figure 8** represents the index of the critical points of the spine, which identifies the data points at different positions on the spine. The vertical axis represents the curve deviation value, which is dimensionless and reflects the degree of deviation between each key point and the standard anatomical curve. The standard anatomical curve is the ideal spinal morphology. The curve before optimization shows a large deviation (MSE = 0.0139), while the optimized curve shows a smaller deviation (MSE = 0.0009), indicating that the spinal morphology is significantly improved.

3.2. Stress and force evaluation

The finite element model of the patient's spine and surrounding tissues is constructed using ANSYS Workbench to simulate the stress distribution under different sitting postures and weight conditions, focusing on the stress concentration areas of the intervertebral disc and bones. The optimized seat geometry and support point distribution, as well as their influence on the area of high-stress areas, distribution uniformity, and local pressure, are analyzed. The results are shown in **Table 1**.

Table 1. Stress distribution and force evaluation.

Area	Max stress before optimization (MPa)	Max stress after optimization (MPa)	High-stress area (cm^2)	Stress distribution uniformity (%)	Local pressure relief (%)
Lumbar area	65.3	48.7	−15.2	+25.3	−19.3
Intervertebral disc	56.1	42.4	−12.4	+28.1	−24.6
Upper back area	45.8	38.1	−9.7	+30.4	−16.8
Lower back area	52.6	45.3	−13.1	+28.4	−13.8
Sacral area	59.2	51.5	−14.3	+22.5	−12.9

The results in **Table 1** show that the optimized orthopedic seat significantly improves the stress distribution in each area. The maximum stress in the lumbar area is reduced from 65.3 MPa to 48.7 MPa; the area of the high-stress area is reduced by 15.2cm^2; the stress uniformity is improved by 25.3%; the local pressure is reduced by 19.3%. The maximum stress of the intervertebral disc is reduced from 56.1 MPa to 42.4 MPa; the area of the high-stress area is reduced by 12.4cm^2; the stress uniformity is improved by 28.1%; the local pressure is reduced by 24.6%. The maximum stress in the upper back is reduced from 45.8 MPa to 38.1 MPa, and the stress uniformity is increased by 30.4%. Although the maximum stress in the lower back decreases slightly, the local pressure is relieved. The improvement in the sacral area is small, with the maximum stress reduced from 59.2 MPa to 51.5 MPa; the area of the high-stress area is reduced by 14.3cm^2, and the local pressure is relieved by 12.9%. The results verify optimized design's effectiveness, which helps improve patient comfort and rehabilitation effects.

3.3. Pressure relief degree

Finite element analysis is used to record the stress values in specific areas and analyze the changes in pressure in the lumbar spine and sacral areas. The seat optimization for pressure relief in the dynamic sitting posture simulation is verified, and the results are shown in **Figure 9**.

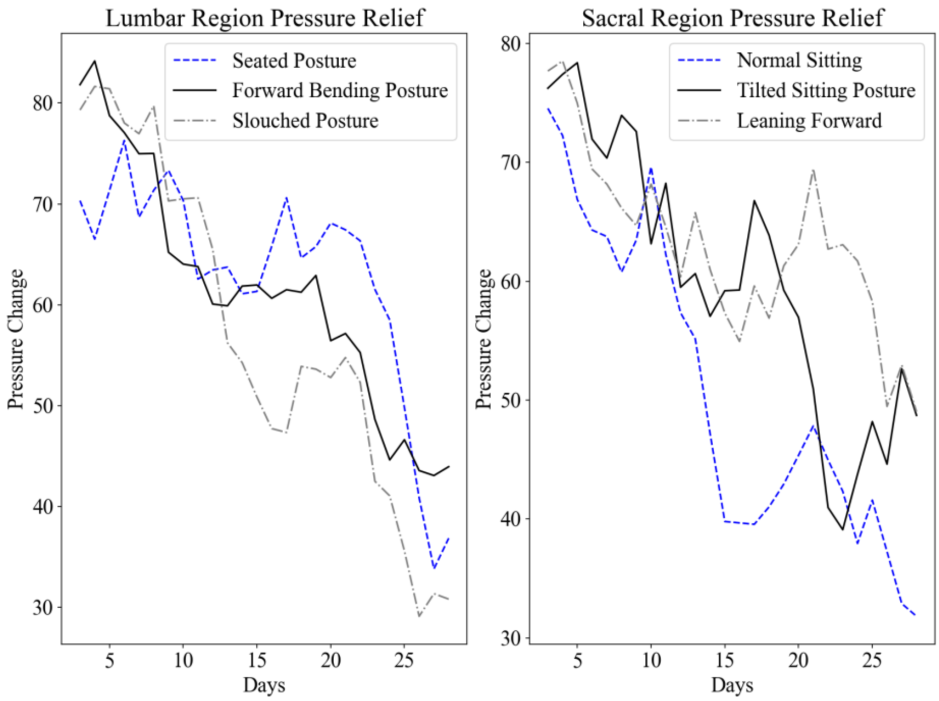

Figure 9. Dynamic pressure relief.

In **Figure 9**, the horizontal axis represents the different test days, and the vertical axis represents the changes in pressure in the corresponding area. For the lumbar spine area in the left figure, the Seated Posture, Forward Bending Posture, and Slouched Posture conditions are focused on; for the sacral area in the right figure, the Normal Sitting, Tilted Sitting Posture, and Leaning Forward conditions are focused on.

As can be seen from the data in **Figure 9**, the pressure values in the lumbar spine and sacral areas have a significant downward trend over time under various sitting posture conditions. On the 3rd day, the pressure value of the lumbar spine in the normal sitting posture is 70.32 MPa, and the value on the 28th day drops to 36.84 MPa. After long-term use of the optimized seat, the pressure in the lumbar spine area can be effectively relieved. The pressure value of the sacral area in normal sitting posture decreases from 74.53 MPa on the 3rd day to 31.83 MPa on the 28th day. The pressure values show a similar downward trend for different sitting postures such as forward leaning and backward leaning. The pressure of the lumbar spine in the forward leaning posture decreases from 81.83 MPa on the 3rd day to 43.93 MPa on the 28th day, and the pressure of the sacrum in the inclined sitting posture decreases from 76.22 MPa on the 3rd day to 48.71 MPa on the 28th day. The data show that the optimized orthopedic seat can effectively reduce the pressure in specific areas and adapt to different sitting posture requirements, providing more comprehensive protection for patients recovering from spinal diseases.

3.4. Statistical significance testing

To better validate the statistical significance of the optimized design in spinal correction, stress distribution optimization, and pressure relief, paired *t*-tests were conducted on the experimental data. By comparing pre- and post-optimization data, differences in spinal curve deviation, maximum stress values, and local pressure were analyzed, and the corresponding p-values were reported. The results of the *t*-test are presented below (see **Table 2**):

Table 2. Statistical analysis results.

Evaluation metric	Pre-optimization value	Post-optimization value	Mean difference	*t*-value	*P*-value
Spinal curve deviation	0.0139	0.0009	−0.013	12.45	<0.001**
Lumbar max stress	65.3	48.7	−16.6	9.84	<0.001**
Intervertebral disc max stress	56.1	42.4	−13.7	8.21	<0.001**
Upper back max stress	45.8	38.1	−7.7	5.72	<0.001**
Lumbar pressure relief	70.32	36.84	−33.48	13.15	<0.001**
Sacral pressure relief	74.53	31.83	−42.7	15.37	<0.001**

The results of the *T*-test show that the optimized orthopedic seat significantly improves spinal health in multiple areas. The reduction in spinal curve deviation (from 0.0139 to 0.0009) demonstrates a marked improvement in spinal alignment, with a strong statistical significance ($P < 0.001$), indicating the seat's effectiveness in correcting spinal curvature. The reduction in maximum lumbar stress (from 65.3 MPa to 48.7 MPa) and intervertebral disc stress (from 56.1 MPa to 42.4 MPa) further underscores the seat's ability to relieve pressure on critical spinal structures, reducing the risk of injury and pain. Additionally, stress in the upper back and sacral areas was also significantly reduced, which enhances overall comfort and posture stability. The pressure relief in the lumbar and sacral regions—dropping from 70.32 MPa to 36.84 MPa and from 74.53 MPa to 31.83 MPa, respectively—shows that the optimized seat adapts well to various sitting postures, offering effective support for patients recovering from spinal diseases. Overall, these findings confirm that the optimized seat design not only improves spinal alignment but also significantly reduces localized pressure, providing better comfort and promoting faster rehabilitation, with all results exhibiting statistical significance ($P < 0.001$).

3.5. Rehabilitation auxiliary effect

The electrical activity data of the patient's muscles before and after use are collected by surface electromyography (sEMG). The changes in the spectrum characteristics are shown in **Figure 10**.

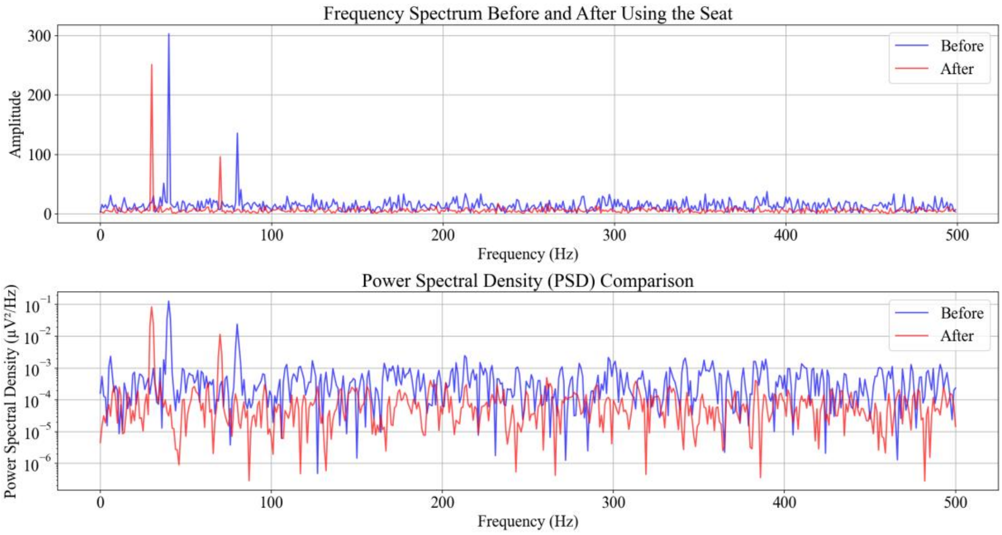

Figure 10. Spectral characteristics of patient muscles before and after using the scheme.

The upper figure of **Figure 10** is a spectrum analysis, where the horizontal axis represents frequency (in Hz), and the vertical axis represents amplitude. **Figure 10** shows the frequency distribution of two groups of electromyographic signals before (blue) and after (red) rehabilitation assistance. In the signal spectrum before use, the blue curve shows a higher frequency component, which is concentrated around 40Hz and has a larger amplitude. At this time, muscle activity is frequent and accompanied by strong noise, which manifests muscle fatigue. The signal after rehabilitation assistance (red curve) shows a lower frequency component in the spectrum, with a peak concentrated around 30Hz and a significantly reduced amplitude, reflecting the reduction and relaxation of muscle activity. It can be seen that after rehabilitation assistance, the frequency of muscle activity decreases, and the amplitude decreases. The seat design effectively helps patients relax their muscles and reduce fatigue.

The lower figure of **Figure 10** is a display of power spectral density (PSD), where the horizontal axis also represents frequency (in Hz) and the vertical axis represents power spectral density (in $\mu V^2/Hz$), that is, the distribution of signal power in different frequency ranges. Semi-logarithmic coordinates are used here, that is, the vertical axis uses a logarithmic scale to present signal changes more clearly. The PSD before using rehabilitation assistance is accompanied by more noise components, reflecting that the muscles are in a state of fatigue. After using rehabilitation assistance, the PSD power density is significantly reduced; the muscles are better relaxed; the noise components are greatly reduced. After the orthopedic seat is optimized, the muscles' high-frequency noise and fatigue-related high-power components are reduced; the power distribution is more concentrated in the low-frequency band; the patient's muscle activity state is significantly improved.

3.6. Satisfaction evaluation

The survey records the subjective feelings of 10 groups of patients (50 people in each group) after using the seat, including comprehensive scores of supports, stability, and touch (1–10). The overall evaluation mean is shown in **Figure 11**.

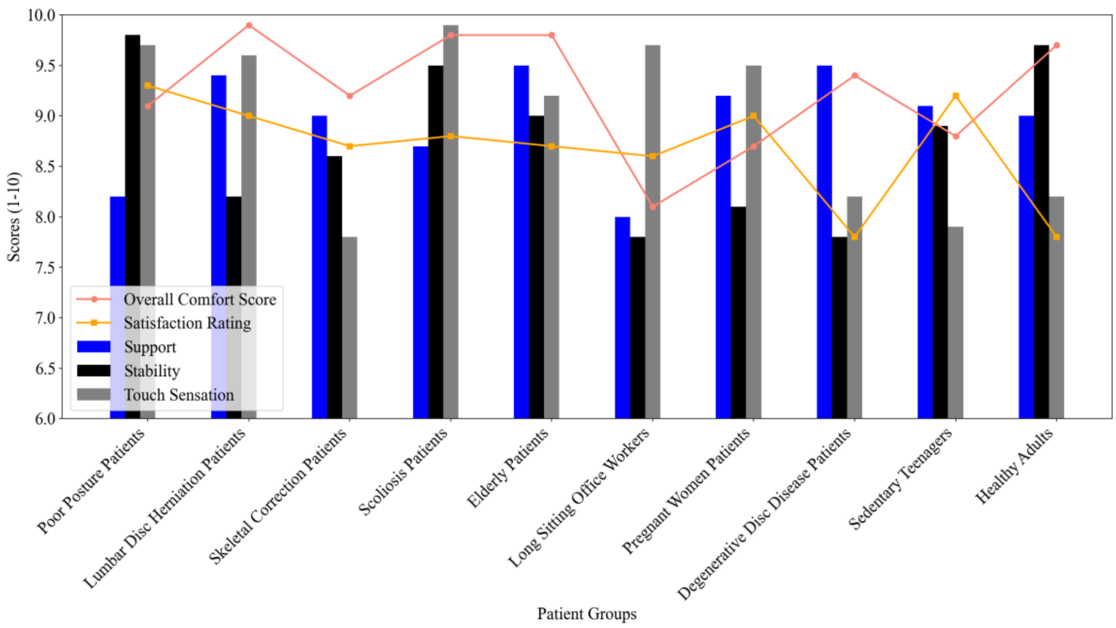

Figure 11. User satisfaction evaluation.

The data results in **Figure 11** show that all types of patients generally give high evaluations to the seat. Patients with lumbar disc herniation score 9.4 and 8.2 in support and stability, respectively, and the overall comfort is 9.9, indicating that the seat provides support while ensuring stability and comfort. Scoliosis patients score the highest for touch (9.9), and the overall comfort score is 9.8, indicating that the seat design can meet their special needs. The elderly patient group scores 9.5 for support, 9.0 for stability, and 9.8 for overall comfort, indicating that the seat significantly improves the quality of life of the elderly. Although office workers who sit for a long time have a slightly lower stability (7.8), the overall comfort score is 8.1, which improves the working environment. The overall comfort of healthy adults is as high as 9.7, maintaining a good level. Ergonomic orthopedic seats designed based on biomechanical principles can effectively improve sitting posture, reduce the risk of spinal diseases, and improve the user experience and quality of life of all types of users.

A detailed analysis of the seating design needs and feedback from different user groups reveals that spinal patients, the elderly, and office workers who sit for long periods have varying requirements, necessitating specific design optimizations. For spinal patients, especially those with lumbar disc herniation and scoliosis, seat support and stability are critical. Data indicates that lumbar disc herniation patients rate the seat's support highly (9.4), suggesting they require additional support to relieve pressure on the lower back. These patients also have higher demands for stability to ensure their posture remains stable and to prevent further spinal damage. Therefore, seat designs must focus on enhancing lumbar support and optimizing the seat's stability to effectively support the natural curvature of the spine and reduce additional pressure during movement.

For the elderly, support and comfort are the most crucial design needs. As elderly individuals often experience bone and muscle degeneration, their comfort expectations are higher. Data shows that elderly patients give high ratings for support and comfort, with an overall comfort score of 9.8, indicating a strong appreciation for the seat's adaptability and comfort. To meet these needs, seats should provide enhanced support for the back and hips while using soft yet supportive materials to reduce discomfort during prolonged sitting. Additionally, since elderly individuals tend to have weaker physical strength, seat height adjustment and tilt functions should be made simpler and more user-friendly.

For office workers who sit for extended periods, the focus of optimization should be on stability, pressure distribution, and comfort. Office workers often remain seated in one position for long hours, which leads to concentrated pressure on the back and hips, contributing to spinal health issues. While office workers rated the seat's overall comfort fairly well (8.1), their stability rating was lower (7.8), indicating a higher demand for stability and continuous support during their work hours. To address this, seat designs can be optimized by enhancing the seat's stability, improving cushion pressure distribution, and incorporating more flexible lumbar support. Additionally, the height and depth adjustment functions should be more precise, allowing office workers to tailor the seat to their specific needs, thereby reducing discomfort from prolonged sitting.

In summary, the varying needs of different user groups require tailored seat design optimizations. For spinal patients, the focus should be on support and stability; for the elderly, the emphasis should be on comfort and ease of use; and for office workers, optimizing stability and pressure distribution is key. By further refining the seat design based on these distinct needs, the seat can better adapt to different user scenarios, ultimately improving spinal health and overall comfort for all types of users.

4. Conclusions

This paper applies an optimization method based on the combination of biomechanics and graphic design for the design of orthopedic seats for patients with spinal diseases. By using MediaPipe Pose to identify critical points of sitting posture, constructing a three-dimensional spine model, and combining it with finite element analysis, the stress distribution of the patient's spine under dynamic sitting posture can be precisely evaluated to optimize the seat geometry and support structure. The results show that the optimized seat significantly reduces the spinal deviation rate. The data results show that the seat optimization method combining dynamic data analysis and three-dimensional modeling can effectively improve the patients' rehabilitation effect and comfort. However, this study is mainly based on experimental data, and the refined adaptation to individual differences still needs to be further optimized. Future research can build upon the current foundation to further explore the integration of real-time feedback technology and artificial intelligence algorithms in intelligent monitoring systems for dynamic posture optimization. This system can monitor posture changes in real-time and automatically adjust the seat's support areas and pressure distribution based on individual differences, meeting various rehabilitation needs. Through continuous learning and optimization, artificial intelligence can enhance the system's personalized adaptability, improving patient comfort and rehabilitation outcomes. Such dynamic adjustment systems not only enhance rehabilitation effectiveness but also have broad applications in posture correction, driving technological advancements in the field.

Ethical approval: Not applicable.

Conflict of interest: The author declares no conflict of interest.

References

1. De Carvalho De, Callaghan Jp. Effect of office chair design features on lumbar spine posture, muscle activity and perceived pain during prolonged sitting. Ergonomics, 2023, 66(10):1465-1476. DOI: https://doi.org/10.1080/00140139.2022.2152113
2. Ademiluyi Adeolu, Aruin Alexander S. Reaching in sitting: The effect of seat design and body manipulations. Work, 2022, 71(1):201-207. DOI: https://doi.org/10.3233/WOR-205114
3. Acharya Bishnu Dutta, Karki Arpita, Prasertsukdee Saipin, Reed Darren, Rawal Lal, Baniya Prem Laxmi, et al. Effect of adaptive seating systems on postural control and activity performance: a systematic review. Pediatric Physical Therapy, 2023, 35(4):397-410. DOI: https://doi.org/10.1097/PEP.0000000000001042
4. Lampe Dario, Deml Barbara. Increasing physical activity in the vehicle with an interactive seating system in a male sample. Ergonomics, 2023, 66(4):536-553. DOI: https://doi.org/10.1080/00140139.2022.2098384
5. Li Zhi, Abd Shukor Rina. Design Issues and Solutions for Improving the Comfort of Neo-Ming Style Chair. Academic Journal of Science and Technology, 2024, 12(3):64-69. DOI: https://doi.org/10.54097/92z30j86
6. Shahriman Muhammad Norman Nurhakim Mohd, Tan Xi Ning, Rasid Mahmud Thaqif Mahmud, Yusri Batrisyia Inanda Sari, Abdul-Kadir Nurul Ashikin, Safri Norlaili Mat. Smart Chair Development using ESP32 Microcontroller–A Preliminary Study. Journal of Human Centered Technology, 2024, 3(1):60-66. DOI: https://doi.org/10.11113/humentech.v3n1.69
7. Md Nadzri Norhani, Hamzaid Nur Azah, Chung Tze Yang. Design and development of a wheelchair seating pressure relief reminder system for pressure ulcer prevention among paraplegics. Journal of medical engineering & technology, 2021, 45(7):574-581. DOI: https://doi.org/10.1080/03091902.2021.1936238
8. Jeong Haeseok, Park Woojin. Developing and evaluating a mixed sensor smart chair system for real-time posture classification: Combining pressure and distance sensors. IEEE Journal of Biomedical and Health Informatics, 2020, 25(5):1805-1813. DOI: https://doi.org/10.1109/JBHI.2020.3030096
9. Wang Yimei, Vatandoost Hossein, Sedaghati Ramin. Development of a Novel Magneto-Rheological Elastomer-Based Semi-Active Seat Suspension System. Vibration, 2023, 6(4):777-795. DOI: https://doi.org/10.3390/vibration6040048
10. Zhang Huizhong, Yang Zhi. Research on dynamic comfort maintenance by measuring lower limb edema and seat pressure during simulated seated sleep in flight. International Journal of Occupational Safety and Ergonomics, 2024, 30(1):72-83. DOI: https://doi.org/10.1080/10803548.2023.2232635
11. Tanoue Hironori, Mitsuhashi Toshitaka, Sako Shunji, Inaba Ryoichi. An exploratory study on the impact of static and dynamic sitting postures on lumbar and pelvic mobility during visual display terminal work. Journal of Physical Therapy Science, 2021, 33(5):406-412. DOI: https://doi.org/10.1589/jpts.33.406
12. Keerthana J, Krishna R Harish, Krishnamoorthy M, Hariharan R, Kumaresan R. Design and analysis of lower limb Assistive Exoskeleton. Asian Review of Mechanical Engineering, 2022, 11(1):18-28. DOI: https://doi.org/10.51983/arme-2022.11.1.3285
13. Zehr Jackie D, Noguchi Mamiko, Fok Donna J, Callaghan Jack P. Mechanical work and energy of sit-to-stand and stand-to-sit transitions performed with traditional and dynamic office chair designs. Work, 2023, 76(1):303-313. DOI: https://doi.org/10.3233/WOR-220333
14. Wang Jianquan, Hafidh Basim, Dong Haiwei, El Saddik Abdulmotaleb. Sitting posture recognition using a spiking neural network. IEEE Sensors Journal, 2020, 21(2):1779-1786. DOI: https://doi.org/10.1109/JSEN.2020.3016611
15. De Mare Lieke, De Groot Bas, De Koning Fleur, Geers Richard, Tetteroo Daniel. The influence of a contoured seating base on pressure distribution and discomfort. Disability and Rehabilitation: Assistive Technology, 2023, 18(1):1-7. DOI: https://doi.org/10.1080/17483107.2021.1892841
16. Nguyen Teron, Nguyen-Phuoc Duy Q, Wong Yiik Diew. Developing artificial neural networks to estimate real-time onboard bus ride comfort. Neural Computing and Applications, 2021, 33(10):5287-5299. DOI: https://doi.org/10.1007/s00521-020-05318-3
17. Ahmad Nooraziah, Ismail Ahmad Rasdan, Mohamad Darliana, Palate Nur Syakina Sonie, Kamaruzzaman Azmul Fadhli.

Improving Classroom Chairs for Student Comfort and Health: An Ergonomic Approach. Journal of Human Centered Technology, 2024, 3(1):22-28. DOI: https://doi.org/10.11113/humentech.v3n1.65

18. Hu Qisong, Tang Xiaochen, Tang Wei. A smart chair sitting posture recognition system using flex sensors and FPGA implemented artificial neural network. IEEE Sensors Journal, 2020, 20(14):8007-8016. DOI: https://doi.org/10.1109/JSEN.2020.2980207
19. Mizumoto Teruhiro, Otoda Yasuhiro, Nakajima Chihiro, Kohana Mitsuhiro, Uenishi Motohiro, Yasumoto Keiichi, et al. Design and implementation of sensor-embedded chair for continuous sitting posture recognition. IEICE TRANSACTIONS on Information and Systems, 2020, 103(5):1067-1077. DOI: https://doi.org/10.1587/transinf.2019EDP7226
20. Lin Ming-Chyuan, Qiu Guo-Peng, Zhou Xue Hua, Chen Chien-Nan. Using Taguchi and neural network approaches in the optimum design of product development process. International Journal of Computer Integrated Manufacturing, 2020, 33(4):343-359. DOI: https://doi.org/10.1080/0951192X.2019.1639218
21. Moshayedi Ata Jahangir, Hosseinzadeh Maziar, Joshi Bhagyashree P, Emadi Andani Mehran. Recognition system for ergonomic mattress and pillow: Design and fabrication. IETE Journal of Research, 2024, 70(2):1956-1974. DOI: https://doi.org/10.1080/03772063.2022.2163927
22. Mahantesh M Math, Rao Kvs Rajeswara, Chandra Ac Prapul, Vijayakumar Mn, Nandini B, Prasad C Durga, et al. Design and modeling using finite element analysis for the sitting posture of computer users based on ergonomic perspective. International Journal on Interactive Design and Manufacturing (IJIDeM), 2024, 18(8):5875-5891. DOI: https://doi.org/10.1007/s12008-023-01383-9
23. Radwan Ahmed, Hall Jessica, Pajazetovic Ariana, Gillam Owen, Carpenter Duane. Alternative Seat Designs-A Systematic Review of Controlled Trials. Professional Safety, 2020, 65(03):39-46.
24. Trivers Neil C, Carrick Christopher A, Kim Il Yong. Design optimization of a business aircraft seat considering static and dynamic certification loading and manufacturability. Structural and Multidisciplinary Optimization, 2020, 62(6):3457-3476. DOI: https://doi.org/10.1007/s00158-020-02650-z
25. Pehnec Igor, Marinic-Kragic Ivo, Vucina Damir. Robust evolutionary shape optimization for ergonomic excellence based on contact pressure distribution. Computer Methods in Biomechanics and Biomedical Engineering, 2020, 23(13):945-958. DOI: https://doi.org/10.1080/10255842.2020.1774751
26. Colley Mark, Jansen Pascal, Rukzio Enrico, Gugenheimer Jan. Swivr-car-seat: Exploring vehicle motion effects on interaction quality in virtual reality automated driving using a motorized swivel seat. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, 2021, 5(4):1-26. DOI: https://doi.org/10.1145/3494968
27. Liaqat Sidrah, Dashtipour Kia, Arshad Kamran, Assaleh Khaled, Ramzan Naeem. A hybrid posture detection framework: Integrating machine learning and deep neural networks. IEEE Sensors Journal, 2021, 21(7):9515-9522. DOI: https://doi.org/10.1109/JSEN.2021.3055898
28. Lepora Nathan F, Lloyd John. Pose-based tactile servoing: Controlled soft touch using deep learning. IEEE Robotics & Automation Magazine, 2021, 28(4):43-55. DOI: https://doi.org/10.1109/MRA.2021.3096141
29. Zhang Jianfeng, Gong Kehong, Wang Xinchao, Feng Jiashi. Learning to augment poses for 3D human pose estimation in images and videos. IEEE Transactions on Pattern Analysis and Machine Intelligence, 2023, 45(8):10012-10026. DOI: https://doi.org/10.1109/TPAMI.2023.3243400
30. Liu Wu, Bao Qian, Sun Yu, Mei Tao. Recent advances of monocular 2d and 3d human pose estimation: A deep learning perspective. ACM Computing Surveys, 2022, 55(4):1-41. DOI: https://doi.org/10.1145/3524497
31. Wen Yuan. Optimization design of biomechanical parameters based on advanced mathematical modelling. Molecular & Cellular Biomechanics, 2024, 21(3):463-463. DOI: https://doi.org/10.62617/mcb463
32. Sharma Rakesh Chandmal, Sharma Sakshi, Sharma Sunil Kumar, Sharma Neeraj, Singh Gurpreet. Analysis of bio-dynamic model of seated human subject and optimization of the passenger ride comfort for three-wheel vehicle using random search technique. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, 2021, 235(1):106-121. DOI: https://doi.org/10.1177/1464419320983711
33. Wang Qichao, Huo Yihuan, Xu Zheng, Zhang Wenjie, Shang Yujun, Xu Hongmei. Effects of backrest and seat-pan inclination of tractor seat on biomechanical characteristics of lumbar, abdomen, leg and spine. Computer methods in biomechanics and biomedical engineering, 2023, 26(3):291-304. DOI: https://doi.org/10.1080/10255842.2022.2062229
34. Zhao Leilei, Yu Yuewei, Cao Jianhu, Zhou Weiwei. Nonlinear coupled dynamic modelling of driver-seat-cab system and biomechanical behaviour prediction. Strojniški vestnik-Journal of Mechanical Engineering, 2022, 68(2):90-100. DOI:

https://doi.org/10.5545/sv-jme.2021.7429

35. Wu Hequan, Hou Haibin, Shen Ming, Yang King H, Jin Xin. Occupant kinematics and biomechanics during frontal collision in autonomous vehicles—can rotatable seat provides additional protection?. Computer Methods in Biomechanics and Biomedical Engineering, 2020, 23(5):191-200. DOI: https://doi.org/10.1080/10255842.2019.1710496
36. Desai Raj, Guha Anirban, Seshu Pasumarthy. An appropriate biomechanical model of seated human subjects exposed to whole-body vibration. Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, 2021, 235(4):586-601. DOI: https://doi.org/10.1177/14644193211039406
37. Xiang Xinhao, Zhang Ke, Qin Yi, Ma Xingchen, Dai Ying, Zhang Xiaoqing, et al. Smart Cushions with Machine Learning-Enhanced Force Sensors for Pressure Injury Risk Assessment. ACS Applied Materials & Interfaces, 2024, 16(29):38466-38477. DOI: https://doi.org/10.1021/acsami.4c05964
38. Paquin Clemence, Rozaire Julie, Chenu Olivier, Gelis Anthony, Dubuis Laura, Duprey Sonia. Studying mechanical load at body-seat interface during dynamic activities such as wheelchair propulsion: a scoping review. Disability and Rehabilitation: Assistive Technology, 2024, 19(5):1879-1889. DOI: https://doi.org/10.1080/17483107.2023.2248184
39. Dong Ruichun, Tang Shengjie, Cheng Xiang, Wang Zongliang, Zhang Peibiao, Wei Zheng. Influence of foot excitation and shin posture on the vibration behavior of the entire spine inside a seated human body. Computer Methods in Biomechanics and Biomedical Engineering, 2024, 27(12):1664-1679.
40. Habegger Janik, Govers Megan E, Hassan Marwan, Oliver Michele L. The Development of a High-Static Low-Dynamic Cushion for a Seat Containing Large Amounts of Friction. Vibration, 2024, 7(2):388-406.
41. Kyeong Seulki. Analysis of the Impact of Chair Tilt Function on Users' Biometric Signals and Comfort. Journal of Biomedical Engineering Research, 2024, 45(2):75-80.
42. Singh Gajendra, Tewari Vk, Ambuj, Choudhary Vinod. Biomechanical analysis of real-time vibration exposure during mini combine harvester operation: A hybrid ANN–GA approach. Journal of Field Robotics, 2024, 41(7):2441-2454.
43. Alshehri Mansour Abdullah, Van Den Hoorn Wolbert, Klyne David M, Hodges Paul W. Coordination of hip and spine in individuals with acute low back pain during unstable sitting. The Spine Journal, 2024, 24(5):768-782.
44. Wang Xuguang, Grébonval Cyrille, Beillas Philippe. Effect of seat back angle on preferred seat pan inclination for the development of highly automated vehicles. Ergonomics, 2024, 67(5):619-627.