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Multi-physics coupling simulation optimization of gradient elastic distribution on the comfort of supporting force of pregnant women's abdominal support band

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SUMMARY: *In order to solve the problems of insufficient support, local compression and comfort fluctuation in the actual wearing of pregnant women's belly support belt, this paper constructs a computational framework combining digital human body modeling, fabric mechanical representation, multi-physics coupling simulation and gradient elastic optimization. In this study, the abdominal surface characteristics, belt body partition structure, material nonlinear parameters and dynamic attitude conditions were integrated into the model. Through finite element solution, surrogate modeling and comfort evaluation algorithm, the virtual reconstruction and parameter optimization of the support force transfer process of the supporting belt were completed. The results show that the gradient elastic scheme can increase the effective support force to 39.4N, reduce the peak pressure to 4.9 kPa, reduce the pressure dispersion coefficient to 0.18, and achieve a comprehensive comfort index of 0.813, which is better than the uniform elastic scheme, the front support area enhancement scheme and the three-zone elastic scheme. The proposed method can better reveal the action mechanism of gradient elastic distribution on support comfort, and provide a computable and verifiable technical path for the intelligent design and individual adaptation of maternity functional clothing.*

KEYWORDS: *gradient elastic distribution; Pregnant girdle; Multi-physical field coupling; Comfort optimization*

1 Introduction

As digital design, human parameter modeling and intelligent simulation technology continue to enter the field of clothing engineering, the development of maternity functional clothing is shifting from experiential tailoring and repeated try-on to data-driven design mode, model calculation and virtual verification. The abdominal support band for pregnant women is not ordinary elastic clothing. Its mechanism of action involves abdominal support, lumbosacral load reduction, pelvic stabilization and local pressure redistribution. It not only needs to form effective support, but also can not induce distension, tight-marks and movement limitation due to excessive compression. Ho et al. carried out wearing tests and demand analysis on maternity support clothing, and pointed out that belly support products have clear value in alleviating low back pain and improving activity comfort, but the comfort effect will be jointly affected by structural configuration, material elasticity and force distribution uniformity [1-4]. Studies by Kalus et al., Quintero Rodriguez et al., also show that the effectiveness of support equipment

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during pregnancy depends not only on "whether support is provided", but also on the position, duration of support force and the degree of individual differences in adaptation [5, 6].

In recent years, the development of clothing pressure prediction and virtual dressing technology provides a new calculation path for the comfort research of the belly strap. Wong et al. discussed the relationship between fabric mechanical properties and dynamic pressure distribution earlier [12]. Zhang et al., Dan et al., introduced the finite element method into the analysis of the relationship between pressure and displacement of elastic clothing, and proved that virtual simulation could describe the response law between pressure of clothing and deformation of human body in detail [14, 15]. Horiba et al. and Teyeme et al. further combined garment CAD, virtual prototype and finite element analysis to improve the operability and visualization degree of pressure prediction of tight-fitting clothing [16, 18]. However, the existing results mostly focus on hosiery, sports tights or general medical compression products, and lack of attention is paid to the maternal abdominal support band, which has obvious physiological stages, abdominal surface variability and support demand zoning. In terms of methods, material elasticity, contact pressure and surface deformation are often treated separately, and there is a lack of comfort-oriented multi-physics collaborative modeling.

From the perspective of engineering implementation, the key to pregnant women's abdominal support belt is not to simply increase the tensile force in a single area, but to build a continuous gradient elastic distribution by means of computer modeling, so that different areas form a computable balance relationship between elongation, contact pressure and support transfer efficiency. If we only rely on the static sample test, the development cycle is long, and it is difficult to track the nonlinear response caused by the change of abdominal bulge, posture switching, and local force transfer. Based on this, this paper focuses on the main line of "gradient elastic distribution - support force transfer - comfort evaluation", and constructs a multi-physical field coupling simulation and optimization framework for pregnant women's abdominal support band. The elastic parameters of materials, human body surface characteristics, contact boundary conditions and dynamic support indicators are unified into the calculation model, and the finite element analysis and optimization algorithm are combined. The partition elastic configuration of the bracket belt is solved iteratively. This paper attempts to solve three problems: how to establish a multi-field coupled simulation model for pregnant women's body characteristics, how to describe the influence of gradient elastic distribution on the support force path, and how to obtain a better balance between effective support and pressure comfort, so as to provide a computable and verifiable technical basis for intelligent maternity clothing design.

2 Related Research

2.1 Intelligent design and mechanical control technology of pregnant women's abdominal support band

The research on the design of pregnant women's abdominal support band has gradually shifted from the stage of simply relying on experience to adjust the tightness and width of the band, to the refined design with functional partition, pressure transfer and individual adaptation as the core. The early products emphasize the immediate effect of pelvic stabilization or waist and abdomen support, but under different gestational weeks and different body types, the local stretch and support path are often lack of calculable description, so it is difficult to balance the support efficiency and wearing comfort. Szkwara et al. reviewed the feasibility and acceptance of dynamic elastic fabric orthopedic products, and pointed out that the effectiveness of maternity support equipment was closely related to the zoning elastic configuration, use compliance and mechanical response in the active state [7]. Flack et al., Bertuit et al., and Kordi et al., from the perspectives of pelvic girder intervention, pain relief, and stability training comparison respectively, showed that the clinical experience of support products without differentiated regulation for the abdominal and pelvic regions is prone to a dilemma of "support but discomfort" or "comfort but insufficient support" [9-11].

With the development of computer-aided design, 3D human body modeling and virtual pressure prediction technology, the mechanical control of the support belt has begun to have the basis of digital implementation. Venkatraman discussed the accuracy of virtual try-on technology in compression suit pressure prediction, and showed that the coupling of digital human body and material parameters could predict the pressure distribution in key areas before sample garment production [17]. Chen et al., Ye et al., and Shi et al., further analyzed the pore structure, compression transmission and tissue response of elastic fabrics from the perspective of biomechanics, and believed that material nonlinearity, surface curvature and force transmission chain should be considered simultaneously for accurate pressure management [19-22]. This kind of research provides method inspiration for the intelligent design of pregnant women's abdominal support band, which can be expressed as optimized gradient elastic units by means of computer modeling. However, the existing results are mainly for therapeutic compression fabrics or lower limb pressure management [23-25], and the special research on dynamic abdominal deformation and lifting comfort during pregnancy is still insufficient, which also forms the practical basis for further multi-physics field coupling optimization in this paper.

2.2 Support comfort simulation evaluation and virtual testing technology

The research path of supporting comfort has gradually shifted from subjective feeling as the core of wearing evaluation to a comprehensive test system that integrates digital human body, material mechanical modeling and virtual pressure prediction. The evaluation of early pregnancy support products mostly relies on the subjective feedback of subjects on low back pain, pelvic discomfort and activity convenience. Such methods can reflect the real wearing experience, but lack quantitative explanations for key issues such as "where support is generated, where compression is formed, and how support is transmitted along the belt body". Szkwara et al. found in a quasi-experimental study on compression shorts during pregnancy that the pain relief effect was closely related to the stress stability of the clothing in dynamic activities, and the static trying results alone were not enough to judge the long-term comfort of the product [8]. Yick et al. 's research on the relationship between sports bra pressure, skin temperature and wearing comfort also suggests that comfort is not the function of a single pressure value, but the result of the joint action of local pressure, heat and humidity changes and human movement coordination [13]. This means that if the comfort evaluation of the support belt remains at the level of single point measurement or questionnaire feedback, it is difficult to support more detailed structural optimization.

With the development of computer-aided design, 3D human body scanning and finite element solution technology, the virtual testing of clothing has changed from "appearance fitting" to "mechanical response reconstruction". Zhang et al. used curve fitting equation and finite element simulation to analyze the relationship between hosiery pressure and human body deformation, and proved that the pressure distribution of clothing could be continuously predicted by digital model [14]. Dan and Shi further discussed the simulation method of pressure and displacement response of elastic clothing waist, indicating that material nonlinearity and surface curvature would significantly affect pressure results [15]. Horiba et al. combined clothing CAD with finite element analysis software and proposed a hybrid method for pressure estimation of tight-fitting clothing with high elastic materials, which improved the consistency between virtual prediction and actual wearing [16]. In recent studies, Teyeme et al. evaluated the pressure comfort of body-fitting clothing through the virtual cycling clothing prototype, indicating that the virtual sample clothing system has been able to support the input of material parameters, the output of regional pressure and the judgment of wearing suitability [18]. As shown in Table 1, although the existing methods continue to make progress in dynamic testing and pressure prediction, there are still problems of insufficient generalization of model objects and insufficient coupling of comfort indicators for functional products such as pregnant women's abdominal support band, which have the characteristics of abdominal bulge change, support demand partition and posture switching. Therefore, this paper extends the support comfort evaluation to a multi-physical field collaborative analysis of "material elasticity -- contact pressure -- abdominal deformation -- subjective comfort proxy index", so as to improve the explanatory power and usability of virtual testing for actual design optimization.

Table 1: Comparison of existing support comfort simulation evaluation and virtual testing methods

Method Type	Main Technical Basis	Whether Dynamic Posture Is Considered	Pressure Prediction Capability	Comfort Characterization Method	Suitability for Maternity Support Belts
Subjective wearing test	Questionnaires, pain scoring, activity feedback	Partially considered	Weak	Mainly based on subjective perception	Medium
Single-point pressure test	Pressure sensors, local measurement	Relatively weak	Medium	Local pressure value	Medium
Virtual garment fitting	3D human body modeling, garment CAD	Can be considered	Medium	Fit quality and shape change	Relatively high
Finite element mechanical simulation	Material constitutive modeling, contact analysis, numerical solution	Strong	Strong	Pressure field, displacement field, strain field	High
Multi-physics coupling virtual testing	Digital human model + material model + contact computation + comfort surrogate evaluation	Strong	Strong	Collaborative characterization of support force, pressure, deformation, and comfort	Very high

2.3 Deficiencies of existing research and innovations of this paper

Although the existing research on pregnant women's belly support has involved support relief, pressure distribution and virtual trying, most of the methods are still in a decentralized state, and a unified computing framework for comfort optimization has not yet been formed. On the one hand, some studies focus on wearing tests or clinical experience comparison, which can explain whether the product is "effective", but it is difficult to further answer how the gradient elasticity affects the coupling relationship between the support path, local pressure and abdominal deformation. On the other hand, the existing clothing pressure simulation mostly serves general tight-fitting clothing or medical compression products, and lacks consideration of abdominal surface growth, body shape change and zoning support demand during pregnancy. There is still a deviation between the model object and the actual use situation. More importantly, material parameters, structural partitions, contact boundaries, and comfort evaluation are often treated separately, resulting in design iterations that still rely on experience, and the calculation results are difficult to directly translate into the optimization scheme of the support belt.

In view of the above shortcomings, this paper takes computer modeling as the main line, and constructs an integrated research framework of "digital human body modeling, material constitutive characterization, multi-physical field coupling solution-comfort index feed-back, gradient elastic optimization", which can transform the elastic distribution of different regions of the support belt into a computable and iterative parameter set. The innovation points of this paper are as follows: the problem of pregnant women's abdominal support band support is promoted from traditional experience design to multi-field collaborative optimization level; The support force, contact pressure and local deformation were integrated into the unified evaluation system. Combined with numerical simulation and optimization algorithm, the comfort-oriented gradient elastic distribution solution is realized, which provides a more interpretable technical path for the intelligent design of maternity functional clothing.

3 System architecture and algorithm design

3.1 Architecture design of multi-physical field coupling simulation system for pregnant women's abdominal support band

In order to improve the computability and optimization efficiency of the design of pregnant women's abdominal support band, this paper constructs a multi-physical field coupling simulation system for support comfort. The system no longer treats the support band as a single elastic component, but integrates the pregnant woman's abdominal surface, the zoning structure of the band body, the material constitutive parameters, the contact boundary conditions and the comfort feedback into the same calculation framework. As shown in Figure 1, the whole system is composed of data layer, coupling solution layer, evaluation and optimization layer and interactive display layer. Each layer is not linearly stacked, but forms a closed loop through parameter feedback and result correction, so that the gradient elastic distribution can continue to iterate in the virtual environment, and finally converge to a design scheme that takes into account both support stability and wearing comfort.

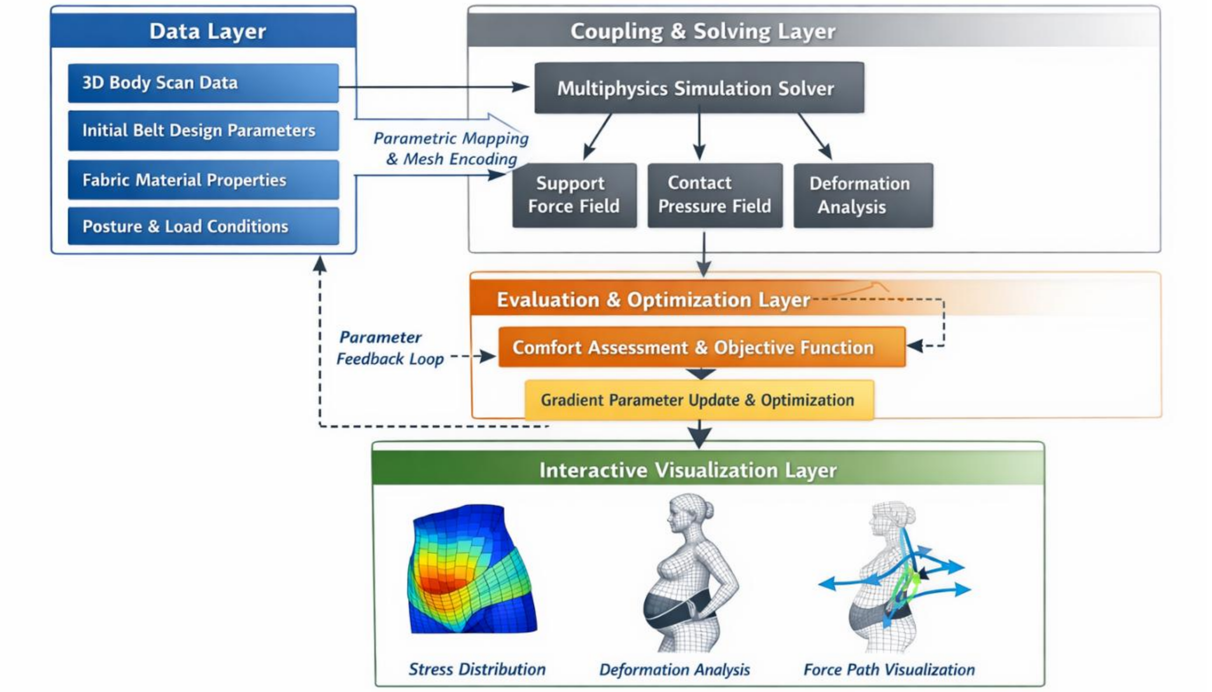

Figure 1: Architecture diagram of multi-physical field coupling simulation system for pregnant women's support belt

In the data layer, the system receives four types of core inputs: the three-dimensional geometric data of the pregnant woman's body surface, the initial structural parameters of the support belt, the mechanical properties of the fabric, and the posture and load conditions. The body surface data can be generated by 3D scanning or parameterized human body model, focusing on extracting geometric features such as abdominal bulge contour, lumbosacral curvature and pelvic lateral boundary. The structural parameters of the girdle include the width of the anterior girdle area, the length of the lateral lumbar area, the Angle of the lower margin and the initial elastic level of different zones. The material parameters are mainly elastic modulus, Poisson's ratio, thickness, areal density and nonlinear tensile curve. In this paper, the system input is uniformly encoded as a state vector for the convenience of subsequent calculation:

$$X = \Phi(B, G_0, \theta, q) \tag{1}$$

where, B represents the geometric feature set of the pregnant woman's body surface, G_0 represents the initial version of the support belt and the partition grid, θ represents the set of material constitutive parameters, q represents the working condition information such as posture, gravity and boundary constraints, and $\Phi(\cdot)$ is the unified parameter mapping function. After this mapping, the data from different sources can be converted into the standard input recognized by the finite element solver.

After entering the coupling solution layer, the system carried out multi-field joint calculation around "structural deformation - contact force transfer - comfort response". The girder body is discretized into shell or membrane elements with partition property, and the abdominal surface is represented by a continuous surface mesh. Considering that the belt is simultaneously affected by pre-stretching, body surface fitting and posture change in the wearing state, this paper uses a contact finite element framework to describe its dynamic response. Its basic equilibrium relation can be written as:

$$\mathrm{M\ddot{u} + C\dot{u} + K(\theta, \alpha)u = F_{ext} + F_{con}} \tag{2}$$

where, u is the node displacement vector, M, C and K represent the mass matrix, damping matrix and stiffness matrix respectively, α represents the gradient elastic configuration parameters of each partition of the supporting belt, $\mathrm{F_{ext}}$ is the external load such as gravity and pre-stretching, and $\mathrm{F_{con}}$ is the normal and tangential force generated by the contact between the belt body and the abdomen. The output of this layer is not only the deformation result, but also the supporting force path, contact pressure field and local strain field. Therefore, "whether the lifting is effective" and "whether the local overpressure" can be determined synchronously in the same model, instead of relying on separate empirical judgments.

The evaluation optimization layer is responsible for transforming the solution results into an objective function that can be used for design update. Considering that pregnant women should not only form sufficient support, but also avoid pressure concentration in the anterior abdomen, near the pubic symphysis or at the lateral waist, this paper establishes a comprehensive comfort index composed of support deviation term, pressure uniformity term and deformation coordination term:

$$\mathrm{J(\alpha) = w_1E_{sup} + w_2E_{pre} + w_3E_{def}} \tag{3}$$

Here, $\mathrm{E_{sup}}$ represents the deviation between the actual support force and the target support interval, $\mathrm{E_{pre}}$ represents the uneven degree of contact pressure distribution, $\mathrm{E_{def}}$ represents the degree of incongruity between abdominal surface deformation and belt body following deformation, and $\mathrm{w_1}$、$\mathrm{w_2}$ and $\mathrm{w_3}$ are weight coefficients. With the goal of minimizing J(α), the system jointly searches for the elastic level, pre-stretch ratio and strip width in different regions, and sets constraints such as maximum allowable pressure, minimum coating stability and structure manufactuability. The result is not a single value, but a set of gradient elastic distribution solutions that can be directly written back to the design.

The interactive display layer mainly undertakes the function of result visualization and design feedback. The system uses Python to complete data preprocessing, parameter calling and optimization process control. With the help of the finite element platform, the three-dimensional pressure cloud map, deformation cloud map and support force transfer trajectory are output, and then the local force differences under different schemes are displayed through the visual interface. The designer can adjust the material partition, the belt boundary or the target support interval, and the system triggers a new round of solution and evaluation updates. The closed loop formed in this way makes the design of the support belt change from "experience modification" to the computational development path of "parameter driven-virtual verification-result writeback". It is also under this framework that the gradient elastic distribution is no longer just an empirical expression of material tightness, but a core variable that can be modeled, compared and optimized, which lays a systematic foundation for subsequent elastic distribution solution methods and comfort algorithm design.

3.2 Optimization method of gradient elastic distribution for support comfort

The optimization of gradient elastic distribution is the core step from empirical structural adjustment to computational fine design. Traditional products usually adopt the whole belt with the same elastic or a small amount of partition differentiation configuration, that is, by improving the overall tensile strength of the front support area or the side waist area to enhance the support effect. This method is easy to make, but it is easy to bring two problems. First, the support force is concentrated in a few areas, resulting in pressure peak at the edge of the lower abdomen or near the pelvis. Second, the rigid and soft transition between different districts of the belt body is discontinuous. When the human body switches between standing, walking or sitting postures, the local deformation will appear abrupt migration, which makes the comfort decrease significantly. For pregnant women, the real effective design is not simply to increase the tensile force, but to establish a smooth, controllable, and manufactuable elastic gradient between the abdominal support area, the lateral lumbar area and the lumbar stability area, so that the support transfer process is both directional and not oversampling sensitive parts. Based on this understanding, the elastic distribution of the support band is transformed from a discrete empirical variable into a continuous computable field, and the constrained optimization is carried out in the multi-physical field coupling environment.

In order to describe the elastic transition characteristics of different regions of the strip, this paper does not directly assign values to each finite element element one by one, but uses basis function expansion to construct the elastic field. Let the parameter coordinates of the midface of the bracket belt be (u,v), then its equivalent elastic distribution can be expressed as:

$$\mathrm{E}(\mathrm{u},\mathrm{v})=\sum_{\mathrm{k}=1}^{\mathrm{m}}\alpha_{\mathrm{k}}\ \psi_{\mathrm{k}}(\mathrm{u},\mathrm{v}) \tag{4}$$

Here, E(u,v) is the equivalent elastic modulus of the band body at the spatial position (u,v), $\psi_{\mathrm{k}}(\mathrm{u},\mathrm{v})$ is the preset partition basis function, α_{k} is the coefficient to be optimized, and m is the number of control nodes. The purpose of this formulation is to compress the originally high-dimensional, discrete and unstable material configuration problem into a set of low-dimensional continuous parameter search problems, while ensuring the interpretability of the elastic transitions between regions. For the anterior abdominal lifting area, the basis function weights are set more centrally in order to form the main support channel for upward lifting. For the side-waist transition region, the elastic decay rate is controlled by a slower basis function change to reduce the "hard edge" effect.

The elastic field representation alone is not enough to complete the comfort optimization, and it is necessary to incorporate the effectiveness of support, pressure uniformity and deformation coordination into the evaluation. To this end, this paper defines the support transfer efficiency index to characterize the bearing contribution of the belt body to the abdominal target area:

$$\Gamma=\frac{\int_{\Omega_{\mathrm{s}}}\mathrm{p}\,(\mathrm{u},\mathrm{v})\,\mathrm{n}_{\mathrm{y}}(\mathrm{u},\mathrm{v})\,\mathrm{d}\Omega}{\mathrm{W}_{\mathrm{b}}} \tag{5}$$

where Ω_{s} is the target support region, p(u,v) is the contact pressure, $\mathrm{n}_{\mathrm{y}}(\mathrm{u},\mathrm{v})$ is the normal component in the support direction, and W_{b} is the equivalent load demand of the abdomen. The larger this index is, the more effectively the band body can convert the elastic potential energy into upward supporting action, rather than expending it inefficiently on lateral binding. Considering that comfort is not equivalent to "the bigger the support, the better", this paper also introduces a pressure fluctuation index to measure the uniformity of local pressure distribution:

$$\Pi=\sqrt{\frac{1}{\mathrm{A}}\int_{\Omega}\mathrm{l}\,(\mathrm{p}(\mathrm{u},\mathrm{v})-\bar{\mathrm{p}})^{2}\,\mathrm{d}\Omega} \tag{6}$$

Here, Ω is the belt body contact area, A is the contact area, and $\bar{\mathrm{p}}$ is the average contact pressure. If Π is too large, it means that the belt body forms high peaks in a few positions, and it is more likely to produce strangulation, swelling and edge indentation in wearing. On the other hand, pregnant women's abdominal support band also needs to adapt to the surface changes caused by abdominal uplift. Therefore, this paper uses the deformation coordination term to describe the matching degree between the band body and the body surface displacement:

$$\Delta = \frac{1}{N}\sum_{i=1}^{N}\left\|u_i^g - u_i^b\right\|_2 \tag{7}$$

where, u_i^g is the displacement of the band body node, u_i^b is the displacement of the corresponding body surface node, and N is the number of contact nodes. When this item is too large, it usually means that the belt is insufficiently considerate or the local pull is too strong, which will weaken the dynamic comfort.

In terms of target construction, this paper does not adopt a single weighting and directly deal with all indicators, but establishes a comprehensive comfort score function based on normalized response:

$$Q(\alpha) = \lambda_1 \tilde{\Gamma} - \lambda_2 \tilde{\Pi} - \lambda_3 \tilde{\Delta} - \lambda_4 \tilde{R} \tag{8}$$

Here, $\tilde{\Gamma}$, $\tilde{\Pi}$, $\tilde{\Delta}$ are the normalized support efficiency, pressure fluctuation, and deformation mismatch indices, respectively, $\tilde{R}$ is the manufacturing complexity penalty term, and $\lambda_1 - \lambda_4$ is the weight coefficient. The reason for introducing $\tilde{R}$ is that the numerically optimal elastic distribution may not be suitable for weaving and sheet cutting implementation. If the elasticity of the adjacent area changes too sharply, the actual product is not only difficult to process, but also weakens the durability. Based on this, this paper sets the gradient constraint of the adjacent control area:

$$|\alpha_{i+1} - \alpha_i| \le \delta, \quad \alpha_{min} \le \alpha_i \le \alpha_{max} \tag{9}$$

Here, δ represents the maximum allowable gradient jump, and α_{min} and α_{max} are the upper and lower bounds of the achievable elasticity of the material, respectively. After this process, the optimization results no longer stay in the ideal simulation space, but can fall back to the real fabric and structure design conditions.

In the solution strategy, this paper adopts a hybrid optimization method of "finite element simulation + surrogate model + iterative search". Instead of blindly traversing in the high-dimensional space, the idea is to generate several sets of initial elastic schemes based on Latin hypercube sampling, call the finite element module to calculate the corresponding Q(α) value, and then use Gaussian process regression to establish an approximate mapping between parameters and comfort scores. For iteration t, the new candidate is given by the acquisition function as follows.

$$\alpha_{t+1} = \arg\max_{\alpha\in\mathcal{D}}[\mu_t(\alpha) + \xi\sigma_t(\alpha)] \tag{10}$$

Here, $\mu_t(\alpha)$ and $\sigma_t(\alpha)$ represent the predicted mean and standard deviation of the surrogate model pair comfort score at round t, ξ is the exploration coefficient, and D is the feasible region satisfying the manufacturing and boundary constraints. This strategy can keep a balance between "finding the known optimal region" and "exploring the unknown potential region", so as to reduce the number of high-cost finite element calls. The whole process is completed by Python parameter scheduling and agent update, the finite element platform is responsible for solving the mechanical response, and the results are sent back to the optimization end to complete a new round of iteration.

Compared with the conventional uniform elastic design, the value of this method is not only reflected in the numerical improvement, but also in the fact that it converts the support experience which is difficult to quantify in the design of the support belt into a computable variable. Through the gradient field parameterization, the designer can clearly know which part of the elastic is stronger and which part of the transition is too fast. Through the objective function decomposition, it can judge whether a scheme is "insufficient support" or "uneven pressure". With the help of surrogate optimization, a better solution can also be approached quickly with a limited simulation budget. In this way, it is not a single optimal value, but a set of interpretable gradient elastic force configuration paths, which provides a stable parameter basis for the establishment of the dynamic support force calculation and comfort evaluation algorithm in the next section.

3.3 Calculation of dynamic support force and design of comfort evaluation algorithm for bracket belt

After completing the gradient elastic distribution modeling, the system also needs to further solve a problem that is closer to the actual wearing: the support effect of the abdominal support band is not constant during the process of standing, walking, turning and sitting, but will continue to fluctuate with the change of abdominal morphology, the stretch redistribution of the belt body and the migration of the contact boundary. If the quality is judged only by the pressure field results at a certain stationary moment, it is often easy to overestimate the actual comfort of the local optimal scheme. Based on this, the working process of the support belt is formulated as a continuous time sequence calculation problem, and the dynamic support force extraction, pressure stability analysis and comfort comprehensive evaluation are synchronously completed on the discrete posture sequence, and the automatic solution and result return are realized by means of a computer program.

The starting point of dynamic support calculation is the temporal expression of pregnant women's wearing state. Suppose that the dressing process is discretized into T instants, and the body posture, abdominal curvature and belt stretching state at each instant constitute the state vector $\mathrm{s_t}$. Considering the small jitter and grid mapping noise often exist in human motion sampling, this paper introduces exponential smoothing mechanism to correct the original state sequence:

$$\tilde{\mathrm{s}}_\mathrm{t} = \rho \mathrm{s}_\mathrm{t} + (1 - \rho)\,\tilde{\mathrm{s}}_{\mathrm{t}-1}, \tag{11}$$

where $\tilde{\mathrm{s}}_\mathrm{t}$ is the smoothed attitude state and ρ is the timing update coefficient. After this process, the system can avoid the sudden jump of the support force calculation caused by the instantaneous attitude disturbance, so that the subsequent results are closer to the continuous mechanical response in the real wearing process. The smoothed state sequence is input into the multi-physics field solver, and the program automatically calls the belt mesh, material parameters and boundary conditions to obtain the contact pressure matrix and node displacement matrix frame by frame.

Based on this, this paper defines the effective support of the support belt to the target support area as the projected cumulative amount of pressure along the preset lifting direction. Let Ω_t^* be the effective contact domain of frame t and d be the abdominal lifting target direction unit vector, then the dynamic support force can be expressed as

$$F_t^{sup} = \int_{\Omega_t^*} p_t\,(x)\, n_t(x) \cdot d\, d\Omega \tag{12}$$

Here, pt(x) is the contact pressure at position x and $n_t(x)$ is the normal vector of the contact surface. Different from the static total pressure, this quantity emphasizes more on "whether the pressure is really transformed into upward support", so that it can more accurately distinguish the two seemingly similar but actually different mechanical states of "tightening" and "support". At the same time, the system also extracts the pressure gradient of the band body in the edge transition zone, which is used to identify the high variation band that may cause the choke mark or friction discomfort:

$$G_t = \frac{1}{A_t}\int_{\Omega_t} \|\nabla p_t(x)\|\ d\Omega \tag{13}$$

where, A_t is the contact area in frame t, and a larger G_t indicates that the pressure change is steeper and the local comfort risk is higher. In this way, when the model judges the support performance, it does not only look at "whether the force is large enough", but also "whether the force is distributed smoothly enough".

The comfort evaluation part continues on the basis of dynamic support. Considering that the wearing experience of pregnant women's belly support belt is usually affected by four aspects: support adequacy, pressure stability, displacement following and timing fluctuation, this paper constructs a frame-level comfort score function:

$$C_t = \beta_1 \exp\left(-\frac{|F_t^{sup} - F^{ref}|}{F^{ref}}\right) + \beta_2 \exp\left(-\frac{G_t}{G^{ref}}\right) + \beta_3 \exp\left(-\frac{D_t}{D^{ref}}\right) + \beta_4 \exp\left(-\frac{V_t}{V^{ref}}\right) \tag{14}$$

where, F^{ref} is the target support reference value, D_t is the relative slip between the band body and the body surface, V_t is the support force fluctuation amplitude at the adjacent time, β_i is the weight coefficient, and satisfies $\sum_{i=1}^{4} \beta_i = 1$. The advantage of this expression is that it does not simply adopt linear superposition, but uses attenuation term to reflect the sensitivity of comfort to deviation: when an index significantly deviates from a reasonable range, the comprehensive comfort score will decline rapidly, which is more in line with the subjective experience in real wearing. For the whole action process, the system takes the time domain average value and introduces the extreme value penalty to obtain the sequence-level comprehensive comfort index:

$$\mathcal{C} = \frac{1}{T}\sum_{t=1}^{T} C_t - \zeta \max_{1\le t\le T}\left(0,\, p_t^{max} - p^{lim}\right) \tag{15}$$

where, p_t^{max} is the maximum local pressure in frame t, p^{lim} is the pressure safety threshold, and ζ is the penalty weight. After this process, even if the average comfort of a scheme is high, as long as there is obvious overpressure in the individual action stage, it will be identified and scored down by the model, so as to avoid the problem of "average value masking local risk".

4 Experiment and simulation analysis

In order to verify the effectiveness of the multi-physical field coupling model and gradient elastic optimization method, an integrated experimental environment of "digital human sample -- structural parameters of the support belt -- mechanical parameters of the material -- dynamic posture conditions" is constructed. The samples were obtained from anonymized body surface data of 36 subjects in the second and third trimester of pregnancy. The gestational age distribution was 24 to 34 weeks, the height range was 1.55 to 1.72 m, and the weight range was 54 to 76 kg. Four kinds of typical postures were extracted from each subject, including standing, supporting phase in walking, turning and sitting, and 144 groups of posture instances were finally formed. The body surface geometry is reconstructed from the structured light scanning data and the parametric human body model, and 60 groups of candidate models are generated according to the above partition idea of the support band. The material library contains five kinds of commonly used elastic knitted fabrics, whose elastic modulus, thickness, areal density and ultimate elongation are calibrated by uniaxial tensile test and input into the simulation system. The calculation part was scheduled in Python 3.10 environment, the finite element solution was completed by Abaqus, and the agent optimization module was implemented by calling NumPy, SciPy and scikit-learn. The main experimental parameters are shown in Table 2.

Table 2: Experimental samples and simulation parameter Settings

Item	Configuration
Number of subjects	36 pregnant participants in the second and third trimesters
Gestational week range	24–34 weeks
Number of posture instances	144 groups
Candidate abdominal support belt schemes	60 groups
Fabric types	5 types of elastic knitted materials
Abdominal and belt mesh scale	About 52,000 elements and 56,000 nodes
Time step	0.02 s
Single-motion simulation duration	8 s
Number of initial sampling schemes	24 groups
Maximum optimization iterations	30 rounds
Surrogate model	Gaussian process regression
Comfort evaluation outputs	Support force, peak pressure, pressure dispersion coefficient, deformation coordination error, and comprehensive comfort index

In the experiment implementation process, this paper sets up four kinds of comparison schemes: uniform elastic scheme, front support area enhancement scheme, three-zone elastic scheme and gradient elastic scheme proposed in this paper. In order to avoid the results reflecting only a single static posture difference, the average performance of all schemes was calculated under four types of motion conditions, and the effective support force, local peak pressure, pressure dispersion coefficient, body-surface deformation coordination error and comprehensive comfort index were jointly compared. The optimization process shows a relatively stable convergence trend. Figure 2 shows that the comprehensive comfort index increased rapidly in the first 10 rounds, from 0.612 to 0.731. After the 15th round reached 0.764, the growth rate began to slow down. It converges to 0.792 in round 30, which indicates that the surrogate model has been able to lock the high comfort interval more accurately. Such changes have strong engineering implications: in the early stage, the main search is to correct the obviously unreasonable high pressure area and low support area, and in the middle and late stage, the problem of uneven transition between adjacent partitions is concentrated, so that the elastic field is gradually approaching the "comfortable and stable" from "available".

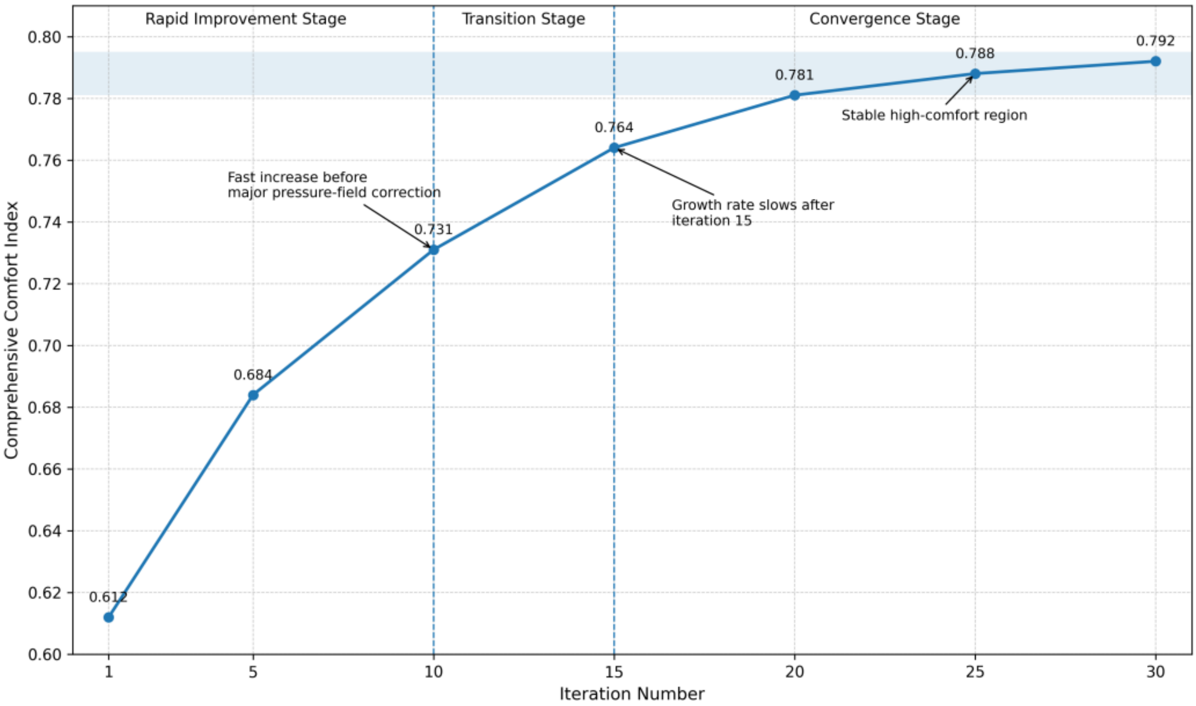

Figure 2: Change curve of comprehensive comfort index during gradient elasticity optimization

From the average results, the gradient elastic scheme is better than the other three schemes in all indicators. Table 3 shows that although the uniform elastic scheme has the simplest structure, the effective support force is only 28.6N, and the pressure dispersion coefficient reaches 0.31, indicating that the belt body is stressed unevenly. The reinforcement scheme of the anterior support area improved the support effect, but formed more obvious pressure concentration at the lower abdominal edge, the peak pressure increased to 8.3 kPa, and the deformation coordination error also expanded to 4.1 mm. The three-zone scheme achieves a certain balance between support and comfort, but there is still the problem of urgent rigid and soft transition in the regional boundary. In contrast, the average effective support force of the gradient elastic scheme reaches 39.4N, which is 37.8% higher than that of the uniform elastic scheme. The peak pressure is reduced to 4.9 kPa, and the pressure dispersion coefficient is only 0.18, which indicates that it can suppress local overpressure while forming an effective lift. The comprehensive comfort index reached 0.813, which was significantly higher than the other schemes. It can be seen that the optimization of the support belt does not focus on the simple "tightening" of a certain area, but on the smooth organization of the support path through the continuous gradient distribution.

Table 3: Comparison of simulation results for different elastic configuration schemes

Scheme	Effective Support Force / N	Peak Pressure / kPa	Pressure Dispersion Coefficient	Deformation Coordination Error / mm	Comprehensive Comfort Index
Uniform Elasticity Scheme	28.6	6.8	0.31	3.7	0.611
Front Support Zone Enhanced Scheme	34.8	8.3	0.35	4.1	0.596
Three-zone Elasticity Scheme	36.7	6.0	0.24	3.0	0.726
Gradient Elasticity Scheme	39.4	4.9	0.18	2.3	0.813

In order to further observe the stability under dynamic conditions, the supporting force fluctuation curves of two representative schemes at different action stages are extracted, as shown in Figure 3. The supporting forces of the uniform elastic scheme were 31.2N, 28.9N, 26.8N, 24.7N and 27.5N in the five stages of standing, walking initiation, walking middle, turning and sitting, respectively, with a large fluctuation range, especially in the turning stage, which indicated that the belt body was prone to force transfer. The corresponding values of the gradient elastic scheme are 38.3N, 37.6N, 36.9N, 35.7N and 36.4N. The overall fluctuation is kept in a small range, and the support continuity is better. In terms of standard deviation, the dynamic volatility of the gradient scheme is 6.9%, while the uniform scheme reaches 10.4%. This difference shows that gradient elasticity does not only improve the pressure image at a certain moment, but also improves the stability of support transmission in motion switching, which is a crucial part of pregnant women's wearing experience that is difficult to be directly captured by static trying.

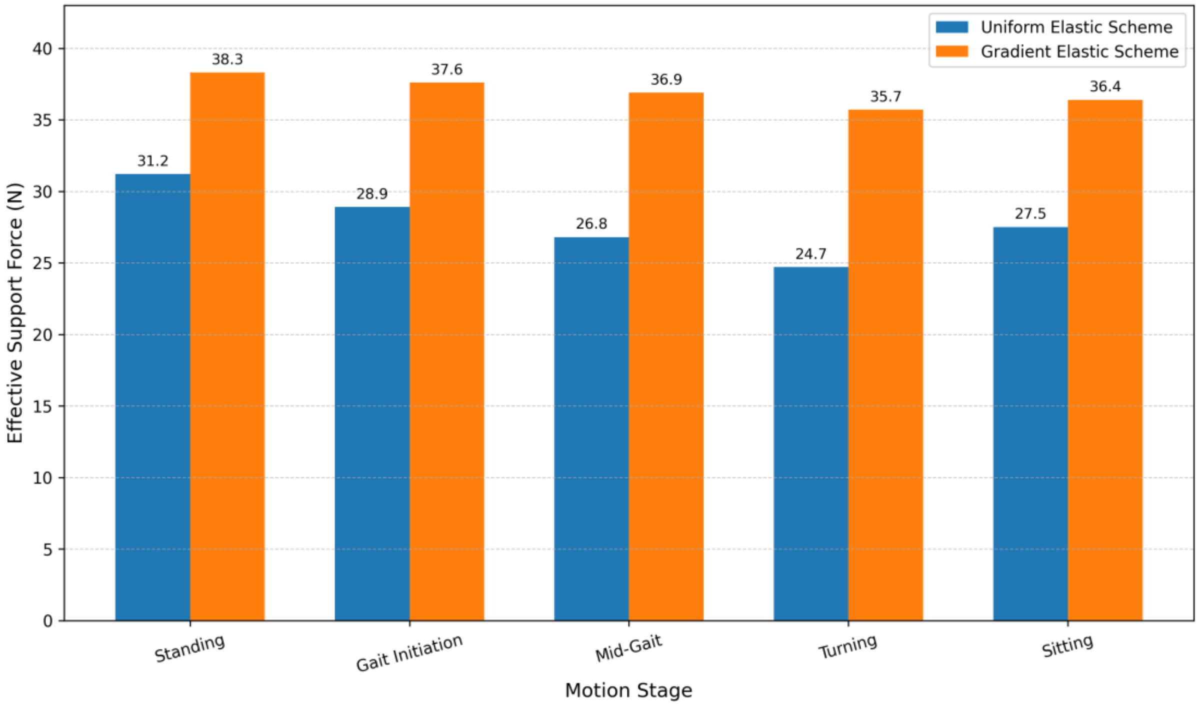

Figure 3: Comparison of effective support force fluctuation of lower support belt in different action stages

In order to test the consistency between the simulation results and the actual wearing performance, this paper selected 8 subjects with obvious differences in body shape to make solid samples, and arranged flexible pressure sensors in the abdominal rest area, lateral waist area and lower edge transition area for control testing. The results show that the relative error between the simulation prediction and the measured average pressure is 8.7%, and the deviation of the peak position is controlled within 5.4 mm, indicating that the established model has good engineering reliability. The errors are mainly concentrated in the sitting posture and turning stage, because there is still some simplification in the local compression of soft tissue and fabric friction behavior. However, from the overall trend, the simulation can identify the high pressure risk area and the insufficient support area more stably, which is enough to support the structural optimization and parameter screening of the support belt.

In summary, the experimental results in this section show that the gradient elastic optimization method based on multi-physical field coupling can achieve a good synergistic effect among support enhancement, pressure uniformity and dynamic stability. Compared with the empirical zoning design, it not only improves the average support level, but more importantly, reduces the pressure peak and motion fluctuation where the source of discomfort is most concentrated. In other words, the optimized support belt does not just "hold", but can maintain a smoother and more coherent support transmission path in different postures. This result has a good echo with the system architecture and algorithm design proposed in the previous section, and also provides a solid experimental basis for the subsequent results discussion and application promotion.

5 Discussion of Results

The simulation results of this study show that the improvement of comfort of pregnant women's abdominal support band by gradient elastic distribution is not achieved by simply increasing the tensile strength of a certain area, but by reconstructing the transfer path of support force through continuous elastic transition. Compared with the uniform elastic scheme, the effective support force of the gradient elastic scheme was increased from 28.6N to 39.4N, with an increase of 37.8%. At the same time, the peak pressure decreased from 6.8 kPa to 4.9 kPa, and the pressure dispersion coefficient decreased from 0.31 to 0.18, indicating that the scheme did not exchange local compression for support enhancement, but achieved a more reasonable match between support efficiency and pressure balance. This result indicates that treating the support belt as a continuous elastic field rather than a discrete elastic partition is more in line with the actual characteristics of abdominal surface change and progressive transmission of support demand during pregnancy.

From the perspective of dynamic working conditions, the gradient scheme shows higher support stability during standing, walking, turning and sitting posture transitions. The effective support force is maintained between 35.7 and 38.3 N in five action stages, and the dynamic volatility is 6.9%, which is lower than 10.4% of the uniform scheme. This difference has clear engineering significance: it is not only the pressure value at a certain time during static wearing that affects the comfort of the support belt, but also whether the support drops suddenly, whether the edge is suddenly tightened and whether the local force is significantly transferred during the action switching. The computational framework established in this paper based on Python scheduling, finite element solving and surrogate model iteration can transform this continuous change process into identifiable and comparable timing indicators, which is also the difficult part of empirical try-on to complete stably. On the other hand, the results also suggest that the current model still needs to be further improved. In the solid sample test, the relative error between the simulation prediction and the measured average pressure is 8.7%, and the deviation of the peak position is 5.4 mm. Although the overall error is in the acceptable range, the error is relatively large in the sitting posture and turning stage, which indicates that the existing model still has a simplified representation of soft tissue compression, fabric friction and local wrinkling evolution. In other words, the proposed method has been able to better identify the undersupport area and the overpressure area, but the description of the local detail response under complex contact conditions is still not completely close to the real wearing state. Further research can introduce more detailed anisotropic material parameters, soft tissue nonlinear models, and adaptive correction mechanisms for individual body size differences to improve the support ability of simulation results for actual product development.

6 Conclusions

Focusing on the problem that it is difficult to balance the support force of pregnant women's belly support belt and wearing comfort, this paper constructs a computational research framework combining digital human body modeling, fabric mechanical representation, multi-physics field coupling solution and gradient elastic optimization. In this study, the supporting belt is no longer simply regarded as an elastic belt body with uniform force, but the abdominal surface change, material nonlinear response, contact pressure migration and dynamic attitude switching are integrated into the simulation system, so that the design of the supporting belt is driven by empirical adjustment of steering parameters and model solution. The system architecture, elastic distribution optimization method and dynamic support comfort evaluation algorithm established on this basis form a relatively complete technical chain, and also provide a clearer realization path for the digital design of maternity functional clothing. The experimental results show that the gradient elastic distribution scheme shows a good synergy between support enhancement and pressure sustained release. Compared with the uniform elastic scheme, the effective support force is increased from 28.6N to 39.4N, the peak pressure is reduced from 6.8kPa to 4.9 kPa, the pressure dispersion coefficient is reduced from 0.31 to 0.18, and the comprehensive comfort index is increased to 0.813. Under dynamic conditions, the gradient scheme maintains a more stable support output in the process of standing, walking, turning and sitting, indicating that the continuous elastic transition can effectively reduce the risk of local force mutation and edge compression. The average relative error between the simulation prediction and the measured pressure is 8.7%, which indicates that the proposed model has good engineering reliability. The significance of this paper is not only to obtain a better parameter configuration of the support belt, but also to prove that the comfort of the support belt can be quantitatively analyzed, virtual verified and iteratively optimized by computer methods. Future research can further improve the nonlinear modeling of soft tissue, the anisotropic representation of fabric and the adaptive mechanism of individual body size, and combine wearable sensing, real-time feedback and lightweight solution technology to promote the pregnant women's abdominal support band from static product design to more targeted intelligent assistant design and individual adaptation application.

References

[1] Ho S S, Yu W, Lao T T, et al. Comfort evaluation of maternity support garments in a wear trial[J]. Ergonomics, 2008, 51(9): 1376-1393.

[2] Ho S S M, Yu W W M, Lao T T, et al. Effectiveness of maternity support belts in reducing low back pain during pregnancy: a review[J]. Journal of clinical nursing, 2009, 18(11):

1523-1532.

[3] Ho S S M, Yu W W M, Lao T T, et al. Garment needs of pregnant women based on content analysis of in-depth interviews[J]. Journal of clinical nursing, 2009, 18(17): 2426-2435.

[4] Ho S, Yu W, Lao T, et al. Maternity Support Garment for the Relief of Lower Back Pain[M]//Medical and Healthcare Textiles. Woodhead Publishing, 2010: 404-414.

[5] Kalus S M, Kornman L H, Quinlivan J A. Managing back pain in pregnancy using a support garment: a randomised trial[J]. BJOG: An International Journal of Obstetrics & Gynaecology, 2008, 115(1): 68-75.

[6] Quintero Rodriguez C, Troynikov O. The effect of maternity support garments on alleviation of pains and discomforts during pregnancy: a systematic review[J]. Journal of Pregnancy, 2019, 2019(1): 2163790.

[7] Szkwara J M, Milne N, Hing W, et al. Effectiveness, feasibility, and acceptability of dynamic elastomeric fabric orthoses (DEFO) for managing pain, functional capacity, and quality of life during prenatal and postnatal care: a systematic review[J]. International journal of Environmental Research and public health, 2019, 16(13): 2408.

[8] Szkwara J M, Hing W, Pope R, et al. Compression shorts reduce prenatal pelvic and low back pain: a prospective quasi-experimental controlled study[J]. PeerJ, 2019, 7: e7080.

[9] Flack N A M S, Hay-Smith E J C, Stringer M D, et al. Adherence, tolerance and effectiveness of two different pelvic support belts as a treatment for pregnancy-related symphyseal pain-a pilot randomized trial[J]. BMC pregnancy and childbirth, 2015, 15(1): 36.

[10] Bertuit J, Van Lint C E, Rooze M, et al. Pregnancy and pelvic girdle pain: Analysis of pelvic belt on pain[J]. Journal of clinical nursing, 2018, 27(1-2): e129-e137.

[11] Kordi R, Abolhasani M, Rostami M, et al. Comparison between the effect of lumbopelvic belt and home based pelvic stabilizing exercise on pregnant women with pelvic girdle pain; a randomized controlled trial[J]. Journal of back and musculoskeletal rehabilitation, 2013, 26(2): 133-139.

[12] Wong A S W, Li Y, Zhang X. Influence of fabric mechanical property on clothing dynamic pressure distribution and pressure comfort on tight-fit sportswear[J]. Sen'i Gakkaishi, 2004, 60(10): 293-299.

[13] Yick K L, Keung Y C, Yu A, et al. Sports bra pressure: effect on body skin temperature and wear comfort[J]. International journal of environmental research and public health, 2022, 19(23): 15765.

[14] Zhang M, Dong H, Fan X, et al. Finite element simulation on clothing pressure and body deformation of the top part of men’s socks using curve fitting equations[J]. International Journal of Clothing Science and Technology, 2015, 27(2): 207-220.

[15] Dan R, Shi Z. Finite element simulation on the relationship between pressure and displacement for the waist of elastic pantyhose[J]. International Journal of Clothing

Science and Technology, 2021, 33(2): 289-301.

[16] Horiba Y, Amano T, Inui S, et al. Proposal of method for estimating clothing pressure of tight-fitting garment made from highly elastic materials: hybrid method using apparel CAD and finite element analysis software[J]. Journal of Fiber Science and Technology, 2021, 77(2): 76-87.

[17] Venkatraman P. Evaluation of the Accuracy and Practicability of Predicting Compression Garment Pressure Using Virtual Fit Technology[J]. Clothing and Textiles Research Journal.

[18] Teyeme Y, Malengier B, Tesfaye T, et al. Fit and pressure comfort evaluation on a virtual prototype of a tight-fit cycling shirt[J]. AUTEX Research Journal, 2023, 23(2): 153-163.

[19] Chen S Y, You J W, Cho Y C, et al. Biomechanical stress distribution of medical inelastic fabrics with different porosity structures[J]. Journal of the Mechanical Behavior of Biomedical Materials, 2023, 147: 106105.

[20] Ye C, Liu R, Ying M T C, et al. Characterizing the biomechanical transmission effects of elastic compression stockings on lower limb tissues by using 3D finite element modelling[J]. Materials & Design, 2023, 232: 112182.

[21] Shi Y, Liu R, Lv J, et al. Biomedical therapeutic compression textiles: Physical-mechanical property analysis to precise pressure management[J]. Journal of the Mechanical Behavior of Biomedical Materials, 2024, 151: 106392.

[22] Shi Y, Ye C, Liu R. A novel optimization approach for bio-design of therapeutic compression stockings with pressure fit[J]. Computers in Biology and Medicine, 2024, 168: 107768.

[23] Liu R, Guo X, Lao T T, et al. A critical review on compression textiles for compression therapy: Textile-based compression interventions for chronic venous insufficiency[J]. Textile research journal, 2017, 87(9): 1121-1141.

[24] nkariya, N. Material, structure, and design of textile-based compression devices for managing chronic edema. Journal of Industria

[25] Yu A, Yick K L. Compression and stretch fit garments[M]//Engineering of high-performance textiles. Woodhead Publishing, 2018: 279-303.