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Research Article

Orthodontic Overcorrection Scheme Generation Based on Improved Multiparticle Swarm Optimization

Tian Ma,[1] **Jiahao Lyu**,[1] **Qin Yang**,[1] **Zhanli Li**,[1] **Yuancheng Li**,[1] **Yanping Chen**,[2] **and Xincheng Ren**[3]

[1]*College of Computer Science and Technology, Xi'an University of Science and Technology, Xi'an 710054, China*
[2]*Shaanxi Key Laboratory of Network Data Analysis and Intelligent Processing, Xi'an University of Posts and Telecommunications, Xi'an 710121, China*
[3]*Shaanxi Key Laboratory of Intelligent Processing for Big Energy Data, Yan'an University, Yan'an 716000, China*

Correspondence should be addressed to Qin Yang; 18792793471@163.com

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The orthodontic treatment often relies on the experience of doctors in traditional methods, and there are often fewer doctors with good experience, which is not conducive to improving the efficiency of patient consultation. Therefore, it has become the mainstream research direction in recent years to assist doctors in improving the efficiency of diagnosis by simulating the dental orthodontic process through computers. The orthodontic process is a multiobjective and high-dimensional path planning problem. To optimize the movement path of multiobjective orthodontics and compensate for the movement efficiency of invisible appliances, a preovercorrection orthodontic motion path scheme based on an improved multi-PSO algorithm was proposed to reduce the dimension disaster and the movement cost and improve the success rate of orthodontic surgery. Firstly, the solution set of the multiobjective particle swarm optimization (MOPSO) algorithm is introduced into the multi-PSO path planning algorithm to obtain the orthodontic movement path. Secondly, by analyzing the movement efficiency of the invisible appliance, tooth displacement compensation is designed and evaluated, and the final orthodontic scheme was generated for patients through the overcorrection method. Finally, the scheme is visualized by VTK visualization. The experimental results show that compared with the multi-PSO algorithm, the improved algorithm can reduce the length of the motion path by 10%, and the rotation angle is reduced by 4%. Meanwhile, the preovercorrection scheme designed can provide movement allowance for the orthodontic process, which guarantees that the optimal orthodontic path obtained by the scheme conforms to the clinical experiment results, ensuring that the tooth can move according to the expected path in the clinical experiment and assuring the success rate of orthodontic treatment.

1. Introduction

Invisible orthodontics use computer-aided technology to obtain orthodontic movement paths and generate orthodontic solutions. The path of each tooth was recorded from the initial position to the ideal position movement, and the amount of movement and rotation was calculated. Finally, the doctor judges the rationality of each step of the orthodontic solutions and determines the final orthodontic solution, which is used for the creation of a virtual tooth orthodontic invisible brace model [1]. Invisible orthodontics can improve the accuracy of orthodontic solutions, which is an important step to help doctors develop orthodontic solutions.

Invisible orthodontic technology includes tooth path planning and orthodontic solution customization. In 1998, invisalign, independently developed by the ALIGN company [2], achieved great success in orthodontic clinics. In 2003, Cadent developed the orthodontic software OrthoCAD [3], which can perform automatic tooth placement by analyzing internal parameters and predicting the entire orthodontic process. However, the data compatibility of the software is not good for widespread promotion. The invisible orthodontic system Invis-OrthoDS enhanced by Bai Yuxing of Capital Medical University [4] has the function of generating a preliminary orthodontic plan. This system divides the orthodontic process into several stages for treatment, which leads to increasing costs. Fan et al. [5] proposed a complete plan for orthodontics, especially in the segmentation and deformation of a single tooth, and achieved remarkable results, while the orthodontic effect of this method is not obvious in the presence of missing teeth. In 2016, Zhang [6] proposed a single tooth arrangement method and a collision detection method in the process of dental orthodontics, but there is still a gap between the collision method and real teeth. Chen et al. [7] proposed formulating a priority plan for orthodontics to find the breakthrough point of orthodontics in advance and then applied the advantage of full-probability coverage of the RRT algorithm to the orthodontic path planning. However, the random collision of the RRT algorithm increases the time complexity of the orthodontic process. With the in-depth study of heuristic algorithms such as genetic algorithm (GA) and simulated annealing algorithm (SAA), it is found that most of the above algorithms have problems such as heavy computation, redundant operation, and long algorithm running time. Therefore, more and more researchers propose using particle swarm optimization (PSO) algorithm to solve the related problems of path planning. PSO algorithm is a global optimization algorithm proposed by simulating bird behavior because its structure is simple and effective, thus widely used in various optimization problems. Therefore, in recent years, the PSO algorithm has been introduced in the research of invisible tooth correction to solve the multiobjective path planning problem. In 2020, Xu et al. [8] established the MOPSO algorithm based on the PSO algorithm which uses a particle to represent the whole teeth for orthodontics. However, this method does not consider the differences between different teeth, which easily leads to correction results that do not conform to conventional treatment methods. Our research group used the multi-PSO algorithm [9] in the early stage to achieve differential orthodontics for different types of teeth, but this method can only achieve local optimization. Considering the multiobjective problem of the orthodontic process, the total swarm communication optimization planning method was introduced to achieve orthodontic differentiation and improve optimization efficiency.

In the process of clinical orthodontics, there is a lag between the actual tooth displacement and the expected tooth displacement, and different tooth movements are affected by periodontal tissues differently. By referring to a large number of medical studies and analyzing the motion efficiency of the appliance from different motion dimensions, Tuncay [10] showed that the average efficiency of Invisalign in incisor and canine depression was 79%. Kravitz et al. [11] showed that Invisalign has the lowest tooth elongation efficiency of all types of tooth movement, with an average of approximately 29.6%. The research group also found that the average correction efficiency of correcting the mesial and distal tilt of the tooth was 40.5%. Simon et al. [12] suggested that the amount of twisting has a significant effect on the efficiency of treatment. Invisalign is designed to twist less than 1.5° and has an orthodontic efficiency of 41.8%, and the efficiency of achieving proximal-medial and distal-medial lateral tooth movement is 88.4%. Djeu et al. [13] showed that the efficiency of controlling the movement of the buccal and lingual sides of the teeth is different; the former is 53.1%, and the latter is 37.6%. In response to this problem, the doctor usually applies 2 mm-3 mm of overcorrection to the orthodontic plan according to the condition of the patient's tooth misalignment, which relies heavily on the orthodontic experience of the doctor. Therefore, an overcorrection method was proposed in this paper to overcome the problem of inefficiency of invisible orthodontics by adding an overcorrection allowance in the orthodontic process.

In this paper, we combine a multiparticle swarm of individualized orthodontics with a single-particle swarm of total swarm particles as a guide, thus shortening the overall orthodontic path to reduce the orthodontic cost. Second, to solve the problem of insufficient performance of invisible aligners, we designed and evaluated orthodontic solutions according to different movement dimensions, which can generate more accurate orthodontic solutions.

2. Modeling of Orthodontic Problems

Orthodontics is a multiobjective movement in a three-dimensional obstructive environment, with the aim of moving the malocclusion to the ideal position through treatment. Due to the peculiarities of the physiological structure of teeth, there are various constraints in translational and rotational movements, and the motion of teeth is described by the motion of rigid bodies in this paper.

Suppose the number of teeth of the patient is n, the current orthodontic stage is m, and the position of the tooth is indicated by the coordinates of the center of the tooth. The rotation center of tooth T_i at the mth stage is $C_{im} = (C_{xi}(m), C_{yi}(m), C_{zi}(m))$, where the subscripts x, y, and z are the three-dimensional coordinates of a tooth. The posture angle is $\delta_{im} = (\alpha_i(m), \beta_i(m), \gamma_i(m))$, supposing that the local coordinates of a single tooth are X_1, Y_1, Z_1 and the global coordinates of all teeth are X_2, Y_2, Z_2. The projection of the aforementioned single tooth in the global coordinates is X_1X_2, Y_1Y_2, and Z_1Z_2, respectively, and the included angles are α, β, and γ. The position of tooth T_i in the mth orthodontic stage can be expressed as $P_{im} = (C_{im}, \delta_{im})$, and the displacement can be expressed by Euclidean distance as

$$S_{im}^2 = \left(C_{xi}(m) - C_{xi}(m-1)\right)^2 + \left(C_{yi}(m) - C_{yi}(m-1)\right)^2 + \left(C_{zi}(m) - C_{zi}(m-1)\right)^2. \tag{1}$$

To simplify the rotation process of tooth, the rotation angle of tooth T_i in the mth orthodontic stage is expressed as

$$\delta_{im} = \left|\alpha_i(m) - \alpha_i(m-1)\right| + \left|\beta_i(m) - \beta_i(m-1)\right| + \left|\gamma_i(m) - \gamma_i(m-1)\right|. \tag{2}$$

The value of single-stage tooth translation S_{im} shall not exceed 0.5 mm, and δ_{im} shall not exceed 3°.

During the orthodontic process, if the orthodontic solutions are not appropriate, the teeth may collide with their adjacent teeth and interfere with the orthodontic effect. Therefore, considering the collision constraint can ensure that the teeth does not interfere with adjacent teeth when moving along the orthodontic path. Let K_{im} be whether the tooth T_i in the mth stage collides or not:

$$K_{im} = \begin{cases} 0, & T_i \text{ does not collide with adjacent teeth,} \\ 1, & T_i \text{ collides with adjacent teeth.} \end{cases} \quad (3)$$

To have a significant change in the collision penalty function when adjacent teeth collide, then given a large constant term L, the penalty function when a collision occurs is expressed as $L * K_{im}$.

The orthodontic cost of n teeth in m stages includes minimum moving path and minimum rotation angle, which are respectively expressed as F_1 and F_2. Under the premise of reasonable planning results, the smaller the value of the two is, the less pain the patient will suffer:

$$F_1 = \min \sum_{i=1}^{n} \sum_{m=1}^{m} S_{im}, \quad (4)$$

$$F_2 = \min \sum_{i=1}^{n} \sum_{m=1}^{m} \delta_{im}, \quad (5)$$

where n and m represent the total number of teeth and the total orthodontic stage, respectively.

3. Orthodontic Path Design

3.1. Improved Multi-PSO Orthodontic Path Planning

3.1.1. Multi-PSO Algorithm. To ensure the motion limitation problem of different orthodontic teeth, the research group adopted a multi-PSO approach for multistage orthodontic planning. By giving different types of teeth different inertial parameters to affect the particle flying speed, they can meet the requirements of orthodontic differentiation in the clinic. However, considering that orthodontics is a multiobjective path planning problem, the above algorithm only achieves the local optimum, and the algorithm is improved due to the above shortcomings.

Suppose, in a D-dimensional search space, there is a multiparticle swarm community consisting of $Z * n$ particles, the position of a current particle ij in the particle swarm of tooth T_i is $X_{ij} = (x_{ij1}, x_{ij2}, \ldots, x_{ijD})$, the velocity of current particle ij is $V_{ij} = (v_{ij1}, v_{ij2}, \ldots, v_{ijD})$, and the optimal position experienced by particle ij in the particle swarm of the tooth T_i is $P_{ij} = (p_{ij1}, p_{ij2}, \ldots, p_{ijD})$. The optimal position experienced thus far by the particle swarm of the tooth T_i is $Q_{ig} = (q_{ig1}, q_{ig2}, \ldots, q_{igD})$, and the different inertia parameters are $\omega_i = |h_i/h|$, where h is the maximum depth of dental arch line, the maximum value of Beta curve on the Y-axis. h_i is the value on the Y-axis of the center point of the ith tooth, as shown in Figure 1, and considering the different inertia parameters for different types of orthodontic velocities, the particle velocity and position update formulas for the tooth particle swarm are

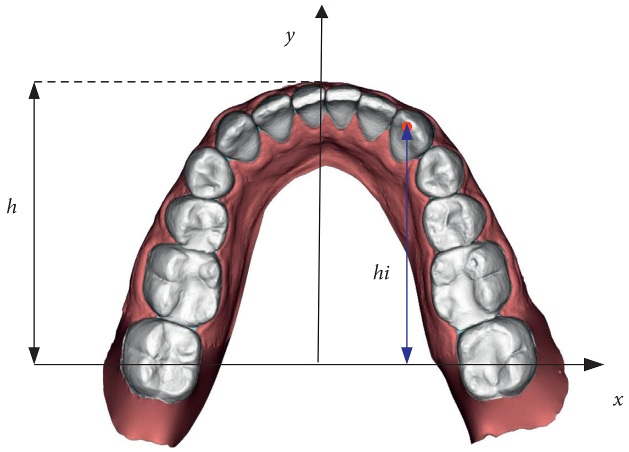

Figure 1: Dental arch depth.

$$\begin{aligned} v_{ijD}(t+1) = {} & \omega_i v_{ijD}(t) + c_1 r_1 \left(p_{ijD}(t) - x_{ijD}(t) \right) \\ & + c_2 r_2 \left(q_{igD}(t) - x_{ijD}(t) \right), \end{aligned} \quad (6)$$

$$x_{ijD}(t+1) = x_{ijD}(t) + v_{ijD}(t+1). \quad (7)$$

Equations (6) and (7): t is the number of iterations, ω is the inertia weight, and the range of values is [0, 1]; c_1 and c_2 are learning factors, usually $c_1 = c_2 = 2$; r_1 and r_2 are random numbers, and the range of values is [0, 1].

According to orthodontic path planning, the teeth need to gradually move closer to the ideal position, the optimization purpose is the shortest path and the minimum rotation, and the constraint is no collision in the path, so the corresponding adaptation function can be constructed as follows:

$$F_{ij} = LK_{im} + \lambda_1 \left(C_{i\text{best}} - C_{ijm} \right) + \lambda_2 \left(\delta_{i\text{best}} - \delta_{ijm} \right) + \lambda_1 F_1 + \lambda_2 F_2, \quad (8)$$

where the first term is the penalty function of a collision, and the value of L in this paper is 10, the second term is the displacement of the tooth from the ideal position and $C_{i\text{best}}$ is the rotation center for the ideal position, the third term is the rotation of the tooth from the ideal position and $\delta_{i\text{best}}$ is the posture angle for the ideal position, and the fourth and fifth terms are the sum of displacement and rotation, respectively, where λ_1 and λ_2 are the corresponding weights. According to orthodontic clinical indications, the path length accounts for a slightly larger proportion of patients in orthodontics than the rotation angle, so the weights in this paper are taken as empirical values 6 and 4, respectively.

To solve the problem that the multi-PSO algorithm cannot achieve the global optimum, this paper combines the solution set of the MOPSO algorithm to realize the correct guidance of the orthodontic process, thereby reducing the planning cost and increasing the orthodontic efficiency.

3.1.2. The Multi-PSO Algorithm with the MOPSO Solution Set. Orthodontic path planning is a complex multiconstrained combinatorial optimization problem in the target space, while meeting the clinical reality is an important prerequisite for orthodontic path planning. This paper improves the guidance strategy based on the previous multi-PSO algorithm of the research group and proposes an algorithm based on multiparticle swarm to introduce the total swarm interaction, which improves the convergence of the algorithm by continuously adding global optimal guidance individuals to the multiparticle swarm. This method takes into account the convergence and personalization of the algorithm to a certain extent in the evolution process.

In the mechanism of the multiparticle swarm, tooth T_i can be coded as $x_i y_i z_i \alpha_i \beta_i \gamma_i$, tooth T_i corresponds to a particle swarm i with an overall global best $p_{ig\text{best}}$, and each particle has a historical best $p_{ij\text{best}}$. According to the priority strategy to traverse n teeth and perform path optimization, the historical optimal solution set of each tooth in the mth stage is obtained as $R_m(p_{1g\text{best}}, p_{2g\text{best}}, \ldots, p_{ng\text{best}})$, according to the termination conditions of the orthodontics to reach the ideal position for ending the orthodontic process. Otherwise, the orthodontic stage is added to continue the orthodontic process, and finally the orthodontic sequence $R_A(R_0, R_1, \ldots, R_l)$ is obtained, where l is the orthodontic stage. Figure 2 shows the orthodontic flowchart of the mth stage of the multi-PSO.

In the MOPSO, n teeth were encoded by $x_1 y_1 z_1 \alpha_1 \beta_1 \gamma_1 x_2 y_2 z_2 \alpha_2 \beta_2 \gamma_2 \ldots x_n y_n z_n \alpha_n \beta_n \gamma_n$, input initial position and ideal position to obtain the solution set: $R_B(R_0, R_1, \ldots, R_l)$. Figure 3 shows the algorithm flow of MOPSO.

The optimal solution $p_{ig\text{best}}$ in each particle swarm in a multi-PSO algorithm is only the intraswarm optimal solution. To further improve the convergence of the algorithm, part of the learning from the overall optimum is added to the basic speed update mechanism so that the particles in the subpopulation can communicate with the overall optimum while they are searching individually, which helps the algorithm converge to the feasible domain quickly.

By improving the flight properties of the particles to communicate with the global, the velocity update formula of the multi-PSO algorithm adds the position information of the MOPSO solution set as a guide to achieving the purpose of overall communication, and the improved velocity update formula is as follows:

$$\begin{aligned} v_{ijD}(t+1) = \omega_i v_{ijD}(t) &+ c_1 r_1\left(p_{ijD}(t) - x_{ijD}(t)\right) \\ &+ c_2 r_2\left(q_{igD}(t) - x_{ijD}(t)\right) \\ &+ c_3 r_3\left(q'_{igD}(t) - x_{ijD}(t)\right), \end{aligned} \tag{9}$$

where the parameters $c_1 = c_2 = c_3 = 2$, r_1, r_2 and r_3 are random numbers between [0, 1], and each particle is affected by the swarm optimum with the same weight as that of the MOPSO particle positional influence and it should be noted that the parameter q'_{igD} is the optimal position that the particle swarm of the tooth T_i has experienced thus far in the MOPSO algorithm, just like q_{igD} in the multi-PSO algorithm. The mth stage orthodontic step of the improved multi-PSO algorithm is shown in Algorithm 1.

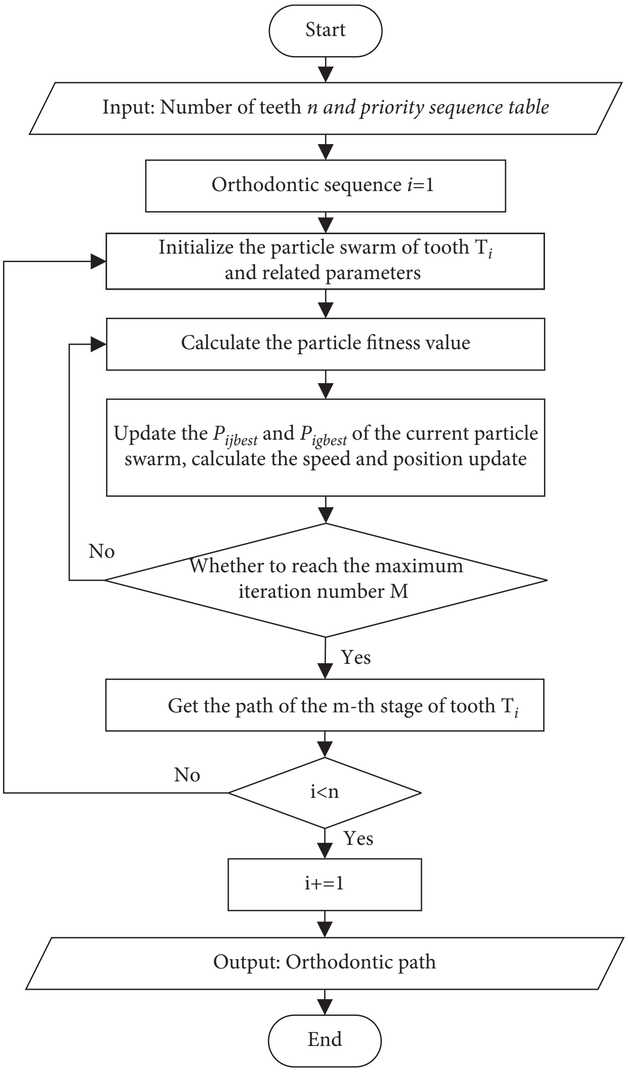

Figure 2: Path planning flowchart of the mth stage of the multi-PSO.

3.1.3. Time Complexity Analysis of Algorithm. The time complexity analysis of a dental orthodontic problem in which the orthodontic stage is S, number of swarm P, number of particles in the swarm Z, and number of swarm iterations N (problem scale) is as follows: in each orthodontic stage, each swarm should be iterated to select the optimal swarm and the calculation of speed and position. The time complexity of the three algorithms is expressed by $O(N)$ as follows.

MOPSO:

$$\begin{aligned} O(S,P,Z,N) &= S * \left(P + \left(P * 3 + O\left(N^2\right) * Z * P\right) + P + P\right), \\ &= S * \left(6P + O\left(N^2\right) * Z * P\right), \\ &= S * Z * P * O\left(N^2\right) + 6SP, \\ &\cong S * Z * P * O\left(N^2\right). \end{aligned} \tag{10}$$

Multi-PSO:

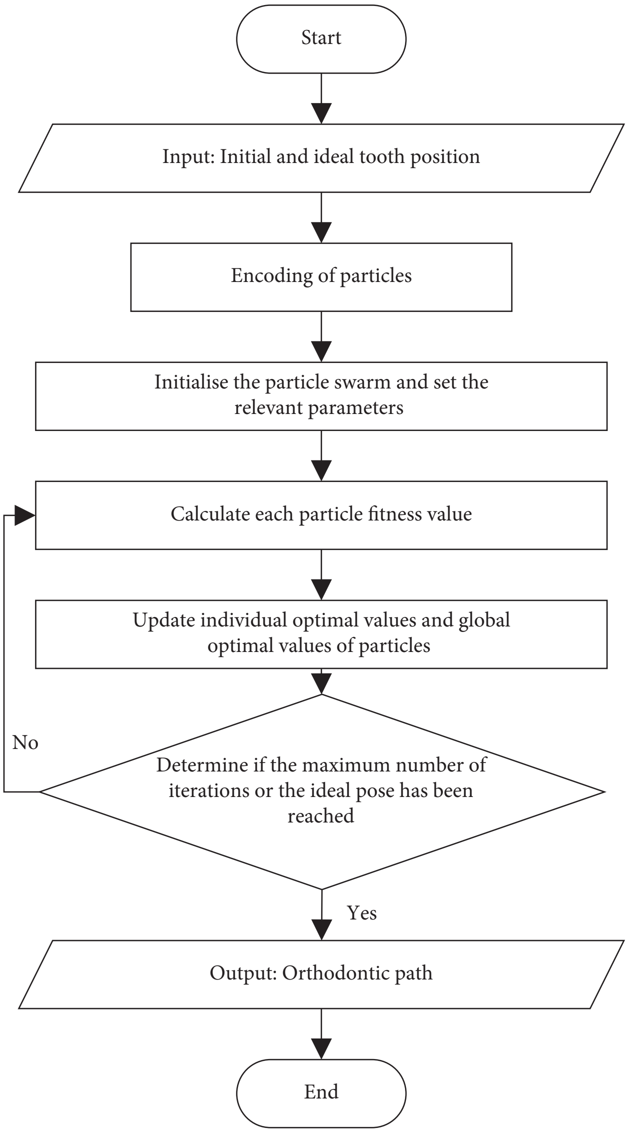

Figure 3: Flowchart of MOPSO.

$$\begin{aligned} O(S,P,Z,N) &= S*\left(P*\left(3+O\left(N^2\right)*Z\right)+P\right),\\ &= S*\left(3P+O\left(N^2\right)*Z*P+P\right),\\ &= S*Z*P*O\left(N^2\right)+4SP,\\ &\cong S*Z*P*O\left(N^2\right). \end{aligned} \tag{11}$$

The improved algorithm is the fusion of the above two algorithms, so the time complexity is approximately equal to the sum of the time complexity of the above two algorithms.

Improved:

$$\begin{aligned} O(S,P,Z,N) &= S*Z*P*O\left(N^2\right)+6SP+S*Z*P\\ &\quad *O\left(N^2\right)+4SP,\\ &\cong S*Z*P*O\left(N^2\right). \end{aligned} \tag{12}$$

Although the time complexity of the three algorithms is approximately the same, it should be noted that the MOPSO algorithm takes a whole maxillary or mandibular tooth as a swarm P, $P=1$. The coding format of a tooth is $xyz\alpha\beta\lambda$, so each time a swarm is updated, the coding dimension of the algorithm reaches 6 times the number of teeth. The multi-PSO algorithm takes one tooth as a swarm, $P=14$, and the tooth coding dimension is 6. In the MOPSO, the whole tooth needs to be calculated for every orthodontic stage, and the entire teeth also need to be calculated for swarm iteration, so the calculation dimension is relatively high. Therefore, in future clinical experiments, although the improved algorithm will achieve a better orthodontic result, it may consume relatively more time for tooth orthodontic.

3.2. Orthodontic Solution Design

3.2.1. Analysis of Orthodontic Efficacy. Due to the "lag" in the orthodontic process, the concept of orthodontic efficacy (efficacy = (actual displacement/expected displacement) × 100%) is proposed. Figures 4 and 5 show the orthodontic displacement and rotation efficacy analysis, respectively.

In Figure 4, assuming that the bracket box of the initial position of the tooth is A, the expected set orthodontic movement position is bracket box C. Due to the orthodontic effectiveness, the actual movement can only be to bracket B. The rotation angle effectiveness is the same as the movement effectiveness, the expected rotation angle is ∠1 in Figure 5, and the actual rotation angle is ∠2.

3.2.2. Orthodontic Solution. When traditional orthodontic planning is completed, the doctor formulates exclusive invisible appliances for different patients based on the orthodontic results, and the final orthodontic effect will be different due to the different ages of the patients. In most cases, dental treatment often lasts as long as one year. During this process, different objective factors often cause dental orthodontics that does not meet the ideal expectations, which lead to the failure of the orthodontic treatment. Therefore, in response to this problem, this paper proposes the overcorrection method to increase the margin of movement of the teeth during orthodontic treatment by intervening in the orthodontic process in advance or during the process. This method reduces the risk of recurrent malocclusion due to improper use of the invisible orthodontic appliance and improves the success rate of orthodontic treatment.

Orthodontic solutions can be divided into two types according to the order of the orthodontics. The first method considers the tooth movement efficiency before orthodontic movement planning, first to determine the ideal tooth position according to the arch line and second to compensate for the lack of tooth movement efficiency by adjusting the ideal tooth position and to compensate for the corresponding values for each of the 6 movement directions of the teeth. The second method does not require the adjustment of the ideal tooth position but adds a small amount of displacement and rotation at each stage to the path already planned in Section 3.1 to ensure that the desired position is achieved at each stage of the movement.

```
Input: initial and ideal tooth position.
Output: orthodontic path solution set.
Step 1: administer orthodontic treatment of teeth by the MOPSO algorithm, and obtain the set of orthodontic solutions $R_B(R_0, R_1, \ldots, R_N)$.
Step 2: calculate the set of dental positional solutions $R_{Bm}(q'_{1gD}, q'_{2gD}, \ldots, q'_{ngD})$ for the $m$th stage of the MOPSO algorithm based on the path solution set $R_B$ obtained in Step 1.
Step 3: orthodontics by the MOPSO algorithm in Section 3.1.3.
Step 3.1: initialize the swarm size to the number of teeth, and the number of particles in the particle swarm to $Z$.
Step 3.2: calculate the value of the fitness function of the particle swarm according to (8) and determine the value of the current particle optimal position $p_{ij\text{best}}$ and the current particle swarm optimal position $p_{ig\text{best}}$.
Step 3.3: update the velocity and position of each particle by (9), and determine whether the maximum number of iterations is reached or whether the ideal position is reached; if not, return to Step 3.2, and if reached, terminate the planning.
Step 4: output the solution set $R_m(p_{1g\text{best}}, p_{2g\text{best}}, \ldots, p_{ng\text{best}})$ of each particle group in the $m$th phase of the particle swarm.
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Algorithm 1: Improved multi-PSO mth stage path planning algorithm flow.

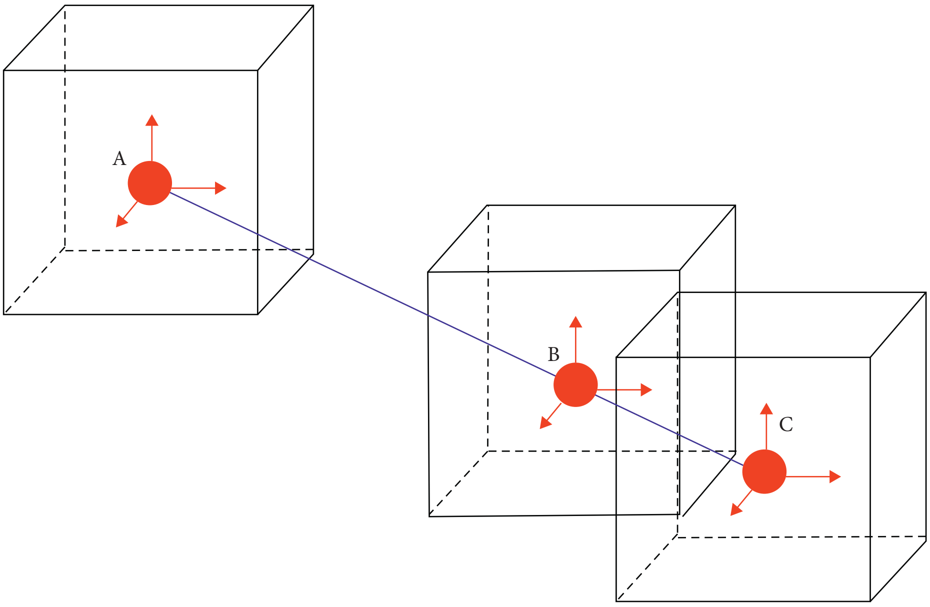
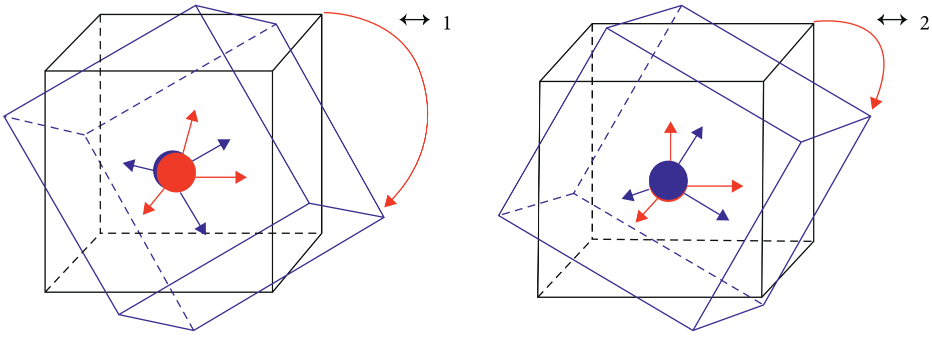


Figure 4: Displacement effectiveness analysis chart.



expected

actual

Figure 5: Rotation angle effectiveness analysis chart.

3.3. Method 1: Preovercorrection. The core of the preovercorrection is the adjustment of the ideal orthodontic position of the teeth before the orthodontic path is planned. In this paper, based on medical statistics, the rotation of the following sample data was increased by 50% of the overcorrection, and the overcorrection displacement was increased by 70%, 10%, 60%, 40%, and 60% for the elongated, depressed, proximal and distal mesial, lingual and buccal sides of the teeth, respectively. Figure 6 shows from left to right the current position of the tooth, the authentic ideal position of the tooth, and the corrected ideal position of the tooth. The preovercorrection process is outlined in Algorithm 2.

3.4. Method 2: Process Overcorrection. Process overcorrection is the addition of excessive movement to the original orthodontic process. The initial and ideal positions of the teeth are known, and path planning is carried out using a combinatorial optimization algorithm to determine the amount of movement and rotation of the teeth at each stage, adding the corresponding motion compensation to the amount of movement at each stage. Figure 7 shows a schematic chart of the orthodontics using the process overcorrection method to displacement motion compensation.

Assume that the initial position of the tooth is *A* and the ideal position is *F*. Using the path planning method to plan its movement path planning, the movement trajectory is *A-B-C-D-E-F*. Considering the movement effectiveness problem, the effectiveness compensation is carried out separately in the direction of the planned movement trajectory in order to enable the tooth to reach the established position at each stage after movement. The effectiveness compensation is carried out separately in the movement direction, the ratio of the compensation value. The same values are used as in method 1, i.e., the ideal position of the tooth at each stage of the correction using the process overcorrection method. For example, if *A* needs to move to the position of B, then the position of B–B' needs to be overcompensated and the final actual trajectory of movement is A-B'-C'-D'-E'-F'. As there is excessive movement in each stage of the tooth, if the tooth movement in that stage exceeds the physiological tolerance, then the stage needs to be split. The process overcorrection is described in Algorithm 3.

4. Experimental Analysis

The experimental hardware environment was developed with an Intel i7 1.80 GHz CPU and 8 GB RAM, and the software environment was a Microsoft Windows 10 operating system, the invisible orthodontic system Orthodontic, MATLAB development environment, and VTK toolkit. In the experiments, the multi-PSO algorithm and MOPSO algorithm are $Z = 50$, the maximum number of iterations $M = 50$, $c_1 = c_2 = 2$, r_1 and r_2 are random numbers between $[0, 1]$, in the improved multi-PSO $c_1 = c_2 = c_3 = 2$, r_1, r_2, r_3 is a random number between $[0, 1]$ and the maximum number of iterations $M = 50$.

4.1. Comparison of the Orthodontic Path Planning Method. In orthodontics, the amount of movement and rotation of the teeth from the initial position to the target position determines the length of the orthodontic period, and the length of the orthodontic path affects the pain suffered by the patient during the orthodontic process; therefore, the smaller the movement and rotation, the better the orthodontic requirements.

The test has been carried out on 30 real teeth data, and five typical groups are selected for experimental verification, which could be used to measure the performance of the algorithm from different angles. And the experimental data of the above three algorithms are the average after 10 independent runs. Table 1 uses the MOPSO algorithm of Xu et al. [8], the previous method of this research group [9], and the improved multi-PSO of this paper to plan the path for 5 groups of mandibular teeth data, and twenty orthodontic stages are planned for the same example. Meanwhile, calculate the path cost of orthodontic stages and the error with the ideal position based on the same example data teeth. The orthodontic cost can be calculated according to (4) and (5) in Section 2 to obtain the total displacement F_1, the total rotation F_2, and the ideal position. The error includes the total error of displacement and the total error of the rotation angle, respectively, expressed as F_3 and F_4. l is the ideal orthodontic position, where the unit of displacement is millimeters (mm) and the unit of rotation angle is the degree (°).

$$\begin{aligned} F_3 &= \sum_{i=1}^{n} \begin{pmatrix} \left(C_{xi}(l) - C_{xi}(m)\right)^2 + \\ \left(C_{yi}(l) - C_{yi}(m)\right)^2 + \\ \left(C_{zi}(l) - C_{zi}(m)^2\right) \end{pmatrix}, \\ F_4 &= \sum_{i=1}^{n} \begin{pmatrix} \left|\alpha_i(l) - \alpha_i(m)\right| + \left|\beta_i(l) - \beta_i(m)\right| \\ + \left|\gamma_i(l) - \gamma_i(m)\right| \end{pmatrix}. \end{aligned} \tag{13}$$

At the same time, the total cost of the ideal position is adopted to evaluate the practicability of the algorithm from all aspects. The ideal total positional cost includes the total displacement cost C_1 and the total rotation angle cost C_2.

$$\begin{aligned} C_1 &= F_1 + F_3, \\ C_2 &= F_2 + F_4. \end{aligned} \tag{14}$$

Among the three path planning methods, the smaller the values of F_1 and $F_{2\ \mathrm{are}}$, the less pain the patient suffers, and the smaller the values of F_3 and $F_{4\ \mathrm{are}}$, the better the orthodontic effect is. Smaller C_1 and C_2 mean that the total cost of orthodontics to the ideal posture is lower. It is shown in Table 1 that the MOPSO algorithm performs better than the other two algorithms in performance F_1 and F_2 in most samples since the algorithm realizes the globally optimal path and reduces unnecessary movement in the process. Similarly, the multi-PSO algorithm has overall advantages in performance F_3 and F_4, due to differentiated treatment among teeth, which optimizes the orthodontic effect of different types of teeth. The improved algorithm combines the advantages of the above two algorithms to realize both

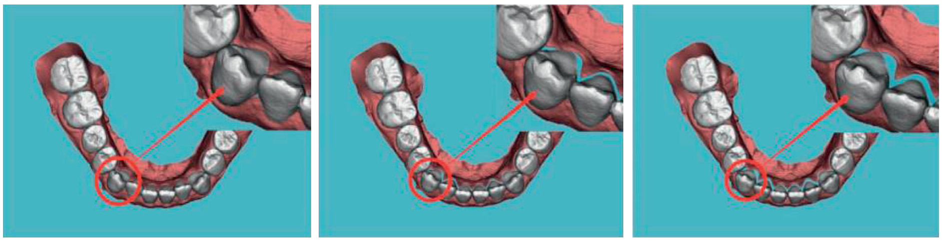


Figure 6: Correction diagram of the ideal position of teeth.

```
Input: initial and ideal tooth position.
Output: orthodontic solutions.
Step 1: calculate the displacement value $S_{im}$ and the rotation angle $\delta_{im}$ from the initial position of the tooth to the ideal position.
Step 2: compensate in the direction of the displacement and the direction of the rotation, employing a reasonable efficiency compensation.
Step 3: obtain the corrected ideal position by compensation.
Step 4: using the initial position of the tooth and the modified ideal position as the input of the path planning, the tooth motion path was obtained using an improved multi-PSO combinatorial optimization algorithm.
```

Algorithm 2: The process of preovercorrection.

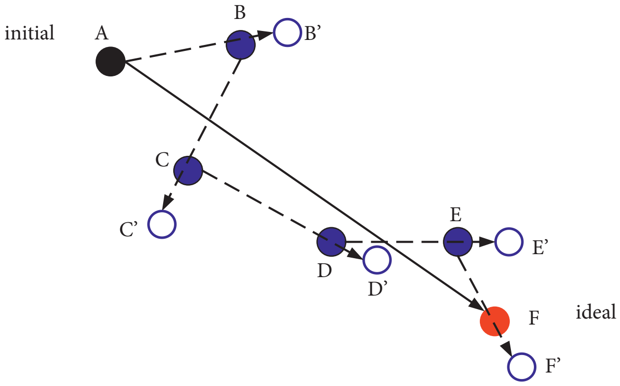


Figure 7: Process overcorrection compensation chart.

```
Input: initial and ideal tooth position.
Output: orthodontic solutions.
Step 1: use the multi-PSO algorithm to obtain the set of path points $T_i\{X_1, X_2, \ldots, X_l\}$ of each stage of the tooth $T_i$.
Step 2: perform compensation calculations from the displacement and rotation of each stage of the different motion dimensions, and then obtain the motion point set $T_i'\{X_1, X_2, \ldots, X_l\}$ after motion compensation.
Step 3: determine whether the amount of tooth movement in the updated orthodontic phase $m$ is more than the physiology can tolerate.
  Step 3.1: if the amount of movement in the phase $m$ of the movement set $T_i'$ exceeds the maximum physiological tolerance, find the displacement and rotation values of all teeth in that phase.
  Step 3.2: find the midpoint of the displacement and half of the rotation angle of all of the teeth in this stage and use this as the motion position for the stage $m + 1$. The motion position of the original stage $m + 1$ is postponed by one stage.
  Step 3.3: update the exercise point set $T_i''\{X_1, X_2, \ldots, X_m, X_{m+1}, \ldots, X_l, X_{l+1}\}$ when the amount of movement is exceeded.
Step 4: generate orthodontic solutions based on the updated set of motion points.
```

Algorithm 3: The process of process overcorrection.

Table 1: Statistical tables of 5 orthodontic results for the groups of arrays.

Method	Performance index	E_1	E_2	E_3	E_4	E_5
MOPSO [8]	F_1 (mm)	**56.08**	34.2	**47.49**	**30.68**	**56.33**
	F_2 (°)	**101.07**	90.96	**50.43**	**43.49**	120.85
	F_3 (mm)	1.68	5.99	6.72	8.31	9.22
	F_4 (°)	4.91	14.84	8.04	14.23	3.31
	C_1 (mm)	57.76	40.19	54.21	38.99	65.55
	C_2 (°)	**105.98**	105.8	58.47	**57.72**	124.16
Multi-PSO [9]	F_1	62.17	45.93	49.81	33	59.47
	F_2	106.03	89.34	57.21	57.7	125.04
	F_3	**0.34**	**4.37**	**2.21**	**5.66**	**4.32**
	F_4	**2.73**	**11.98**	**4.1**	**10.07**	**2.12**
	C_1	62.51	50.3	52.02	38.66	63.79
	C_2	108.76	101.32	61.31	67.77	127.16
Improved	F_1	56.11	**34.12**	47.76	30.91	56.43
	F_2	102.99	**89.05**	52.46	53.71	**120.22**
	F_3	1.57	4.93	2.58	6.01	4.33
	F_4	3.06	12.26	4.73	10.9	3.21
	C_1	**57.68**	**39.05**	**50.34**	**36.92**	**60.76**
	C_2	106.05	**101.31**	**57.19**	64.61	**123.43**

The bold values indicate that comparison is best in a single performance.

orthodontic global processes and differentiated tooth movement. The improved algorithm can achieve the majority of advantages in C_1 and C_2 performance, which indicates that the overall effect of the improved algorithm is obvious and contributes to the optimal clinical experiment results.

Because the original data of the five mandibular teeth models had a great difference, the result of the same performance index had a great difference. To facilitate the analysis of the data in the tables, the results were tallied using statistical averaging, so that the characteristics and advantages of each algorithm can be seen intuitively. The average results are shown in Table 2:

Analyzing the MOPSO algorithm shows that it does not provide differentiated movements for different types of tooth designs, and even though the values of F_1 and F_2 indicate the lowest orthodontic cost, the values of F_3 and F_4 indicate large error values for the distance from the ideal posture; i.e., the algorithm is too idealistic and does not provide good orthodontic results. Both the multi-PSO algorithm and the improved multi-PSO algorithm can personalize orthodontics for patients, but the cost of the orthodontics before the improvement is too large and the orthodontics path is not globally optimal. Under the guidance of the MOPSO's solution set, the improved multi-PSO algorithm reduces the orthodontic path length by approximately 10% and the rotation angle by approximately 4% on average, and also the path could reach the global optimal, which greatly reduces the cost of orthodontics. The difference between the orthodontic effect and the improvement is approximately 1%, which is negligible. The improved algorithm is in the second best in $\overline{F}_1$, $\overline{F}_2$, $\overline{F}_3$, and $\overline{F}_4$, and there is no big difference compared with the best, performing better than the other two algorithms for both C_1 and C_2, and the total cost of orthodontics is minimal, which is beneficial to doctors to achieve better treatment effect in clinical experiments and reduce the pain of patients.

4.2. Evaluation of the Overcorrection Method. In Section 3.2, two orthodontic protocols are proposed, both of which used a 50% increase in the amount of rotation for overcorrection, a 70% increase in overcorrection displacement in the direction of tooth elongation, a 20% increase in overcorrection displacement in the direction of tooth depression, a 10% increase in overcorrection displacement in the mesial and distal mesial directions, a 60% increase in overcorrection displacement for lingual movement, and a 40% increase in overcorrection displacement for buccal movement. Since the values of the effective compensation of the displacement and rotation components are the same, the orthodontic results are the same for both groups of orthodontic solutions. The evaluation of the advantages and disadvantages of the orthodontic solutions focused on the cost of tooth movement, mainly in terms of the amount of rotation and displacement. Table 3 shows the evaluation of the two overcorrection methods and a nonovercorrection method based on improved multi-PSO algorithm path planning for five sample data sets, where the displacement is in millimeters (mm) and the rotation angle is in degrees (°). Note that the experimental results are also averages obtained after 10 independent runs.

According to Table 3, the mean values of the displacement sum of the five groups of data for nonovercorrection, preovercorrection, and process overcorrection were 45.07, 54.41, and 57.45, respectively, and the mean values of the rotation angle sum were 83.69, 101.06, and 125.53, respectively. Compared with the two methods, the increments of the nonovercorrection displacement sum are 20.74% and 27.48%, respectively, and the increments of the rotating sum are 20.76% and 50.00%, respectively. Although the experimental results of the two overcorrection methods were much higher than those of the nonovercorrection method, there were many objective factors in the clinical experiments, such as teeth damage caused by improper eating and wearing of invisible orthodontic appliance, which led to the failure of the orthodontic process. Therefore, considering the existing

Table 2: Analysis of the results of the three orthodontic algorithms.

Method	$\overline{F}_1$ (mm)	$\overline{F}_2$ (°)	$\overline{F}_3$ (mm)	$\overline{F}_4$ (°)	$\overline{C}_1$ (mm)	$\overline{C}_2$ (°)
MOPSO [8]	**44.96**	**81.36**	6.38	9.07	51.34	90.43
Multi-PSO [9]	50.08	87.06	**3.88**	**6.2**	53.96	93.26
Improved	45.07	83.69	4.08	6.63	**49.15**	**90.32**

The bold values indicate that comparison is best in a single performance.

Table 3: Comparison table of overcorrection options.

Method	Performance index	E_1	E_2	E_3	E_4	E_5
Nonovercorrection	F_1 (mm)	56.11	34.12	47.76	30.91	56.43
	F_2 (°)	102.99	89.05	52.46	53.71	120.22
Preovercorrection	F_1	69.32	42.29	54.04	41.34	65.07
	F_2	122.77	98.03	63.09	70.99	150.40
Process overcorrection	F_1	77.99	44.01	60.18	36.78	68.28
	F_2	154.49	133.58	78.69	80.57	180.33

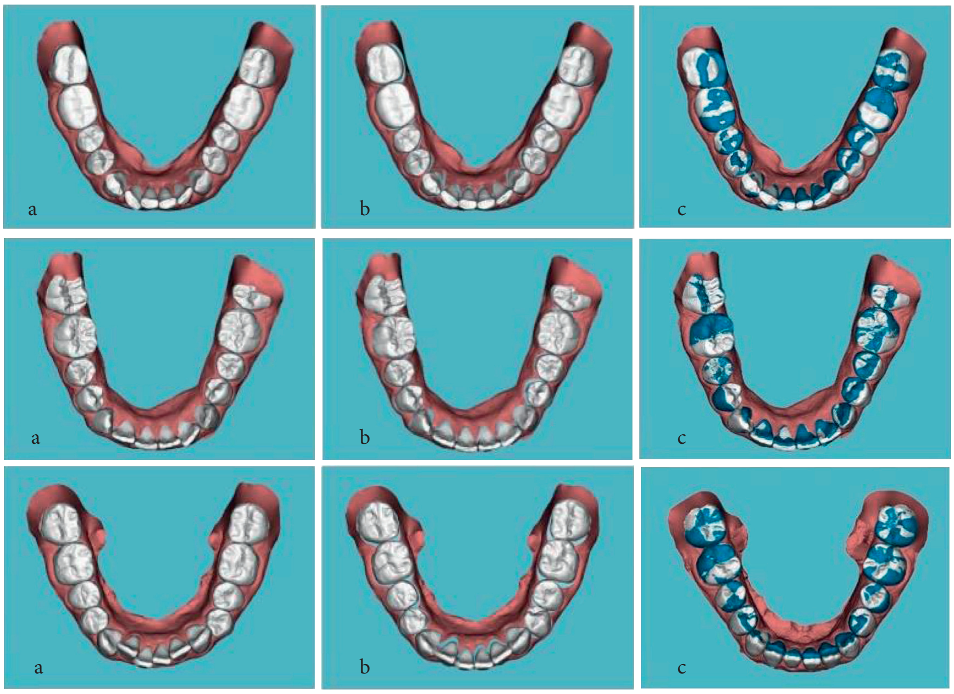


Figure 8: Before and after orthodontic treatment.

objective factors, this paper is designed to use overcorrection methods for the above problems, which provides a movement margin for the orthodontic plan and ensures the effectiveness and variability of clinical experiments. The analysis showed that the displacement and rotation of the preovercorrection were significantly smaller than the values of the process overcorrection, and the preovercorrection was more in line with the actual clinical need after considering the pain suffered by the patients.

4.3. Visualization of the Orthodontic Solution. To visually see the results of the experiment, this section uses the preovercorrection method to visualize the orthodontic process of the teeth. Figure 8 selects three sets of mandibular data to demonstrate the effect of the teeth before and after orthodontics. State *A* is the posture of the mandibular teeth before orthodontics, State *B* is the posture of the teeth after orthodontics, State *C* is the comparison of the posture of the teeth before and after orthodontics (in State *C*, the blue is the preorthodontic posture, and the white is the post-orthodontic). The teeth are arranged neatly and beautifully after orthodontics.

Figure 9 shows nine of the 24 stages of orthodontic treatment for a sample case. In each stage of orthodontic treatment, the teeth move toward the target position according to the tooth movement constraint until the algorithm reaches the termination condition. This method can

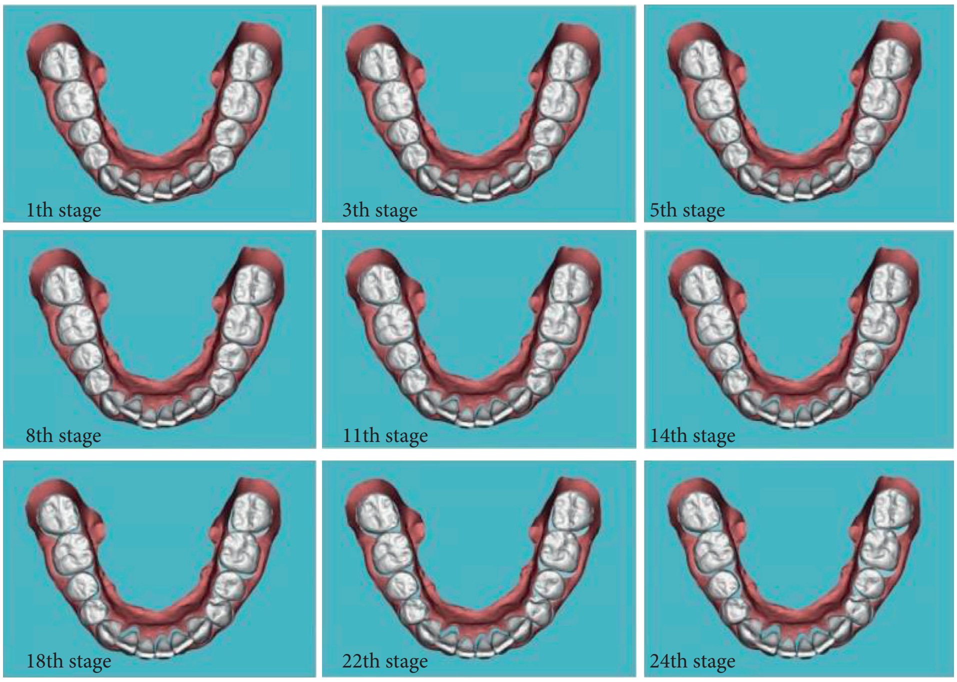


Figure 9: The orthodontic process.

plan a collision-free optimal path for tooth movement and generate an invisible correction plan that meets the requirements of clinical orthodontics.

5. Conclusion

Orthodontic movement path generation is a system, which is an integral part of the invisible orthodontic technology and has received increasing attention from researchers in the fields of computer-aided design and graphics in recent years. This paper proposes a preovercorrection orthodontic motion path scheme based on an improved multi-PSO algorithm. Firstly, considering the personalized movement of different types of teeth, the solution set of the MOPSO algorithm is used as a guiding strategy on the basis of the multiparticle swarm algorithm, which reduces the cost of orthodontics while enhancing convergence and personalization. Secondly, we propose and evaluate two options for the lack of effectiveness of invisible aligners in moving teeth: preovercorrection and process overcorrection. Through experimental evaluation, the orthodontic cost of the preovercorrection option is significantly better than that of the process overcorrection. Then the optimization algorithm proposed in this paper adopts the preovercorrection method to visualize the orthodontic correction process by using the VTK toolkit. Finally, the experimental data verifies that the proposed optimization algorithm has better overall planning results than other algorithms and confirms the effect of clinical experiments to the greatest extent. Therefore, the dental orthodontic program proposed in this paper can help doctors assist in diagnosis, provide effective help in the future, and improve the dental orthodontic path planning in the relevant orthodontic treatment system. Because the improved algorithm is based on the fusion of the above two algorithms, the difference between the global and the local needs to be calculated in the orthodontic process, so the time complexity of the algorithm is high. Because of the physiological structure of the teeth, the occlusal conditions of upper and lower molars were not considered in the above scheme. Under this premise, the orthodontic process can only be divided into two parts: maxillary teeth and mandibular teeth, so the solution still has shortcomings and deserves further investigation.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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