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Research on the Optimization Method of Arm Movement in the Assembly Workshop Based on Ergonomics

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Abstract: In order to improve the work efficiency and comfortability, Ergonomics is used to research the work of the operator in the assembly workshop. An optimization algorithm of arm movement in the assembly workshop is proposed. In the algorithm, a mathematical model of arm movement is established based on multi rigid body movement model and D-H method. The solution of inverse kinematics equation on arm movement is solved through kinematics theory. The evaluation functions of each joint movement and the whole arm movement are given based on the comfortability of human body joint. The solution method of the optimal arm movement posture based on the evaluation functions is described. The software CATIA is used to verify that the optimal arm movement posture is valid in an example and the experimental result show the effectiveness of the algorithm.

1. Introduction

Workshop assembly usually needs the direct participation of people [1-2]. Due to the randomness and subjectivity of the labor itself, it has become a major problem to improve the efficiency of labor. Ergonomics, as a multidisciplinary subject, considers how to improve work efficiency, human health, safety and comfort, and other factors simultaneously so as to achieve multi-objective optimization [3-5]. In view of the advantage of Ergonomics, it is used to study the labor of operator in workshop assembly and to put forward reasonable improvement measures and suggestions [6-7].

The existing ergonomics evaluation methods collect a large number of human physiological parameters, and use the evaluation criteria, such as fatigue degree and energy consumption degree, to evaluate human movement in order to make corresponding improvement measures [8-10]. However, these evaluation methods do not study the movement of human body, which makes it difficult to improve the movement of human body by the evaluation results.

Therefore, an optimization algorithm of human arm movement in the assembly workshop based on ergonomics is proposed. The mathematical model of human arm movement is established, and the evaluation function of movement posture is defined. The optimal movement posture can be obtained from the evaluation results. Experiments and results show the effectiveness of the algorithm.

2. The optimization algorithm of upper limb movement

2.1. The upper limb kinematics model and its solution

The degrees of freedom of the arm and the coordinate systems are established based on D-H method, shown in Figure 1:

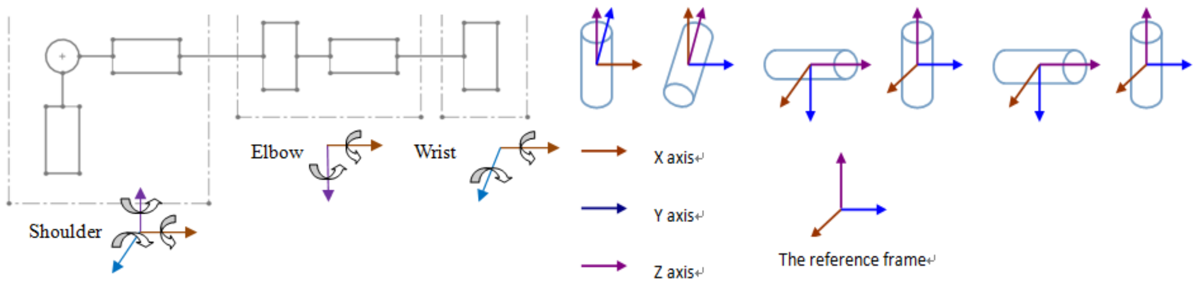

Figure 1. The degrees of freedom of the arm and the coordinate systems based on D-H method

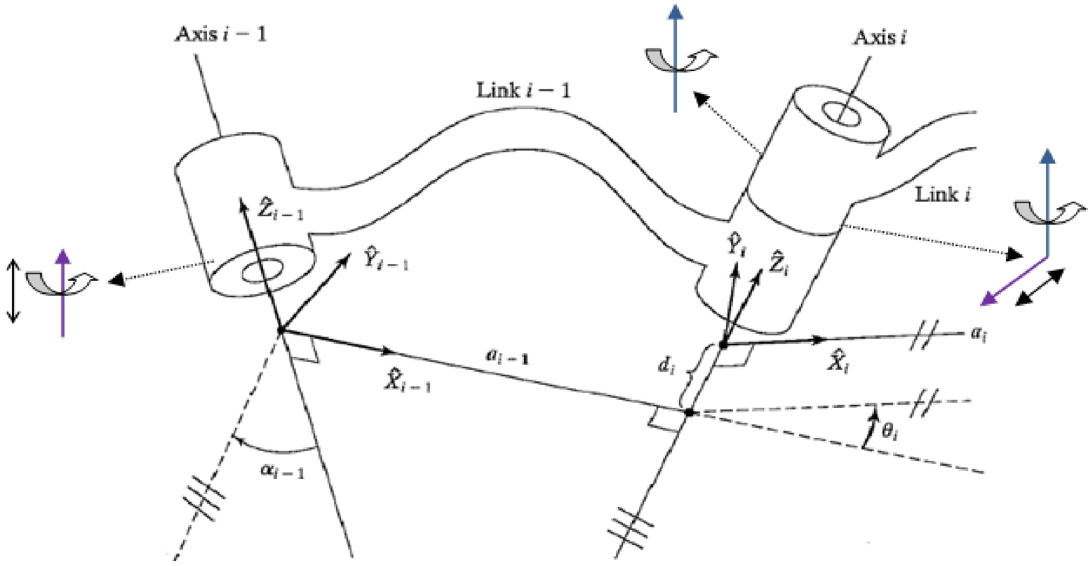

Figure 2. The D-H method of the space connecting rod

D-H method is used to establish the coordinate system of each link, shown in Figure 2. The relative position between the coordinate system $i-1$ and i can use the following four corresponding link parameters to indicate:

(1) Define the distance from the axis Z_{i-1} to the axis Z_i as the connecting rod length a_i, the direction along the axis X_i points in the positive;

(2)Define the angle from the axis Z_{i-1} to the axis Z_i as the coupler-angle α_i $(\alpha_i \in (-\pi, \pi])$, the direction of rotation in the positive of axis X_i points in the positive;

(3) Define the distance from the axis X_{i-1} to the axis X_i as the joint distance d_i, the direction along the axis Z_{i-1} points in the positive;

(4)Define the angle from the axis X_{i-1} to the axis X_i as the joint angle θ_i, the direction of rotation in the positive of axis Z_{i-1} points in the positive;

According to the Figure 1 and Figure 2, the D-H parameters of the arm can be set in Table 1:

Table 1. D-H parameters of the arm

connecting rod i	Joint degree of freedom	Coupler-angle α_{i-1}	Connecting rod length a_{i-1} (mm)	Joint distance d_i (mm)	Joint angle θ_i
1	Shoulder pitch	0°	0	0	θ_1
2	Shoulder swing	-90°	0	0	θ_2
3	Shoulder transfer	-90°	0	d_3	θ_3
4	Elbow pitch	90°	0	0	θ_4
5	Elbow transfer	-90°	0	d_5	θ_5
6	Wrist pitch	90°	0	0	θ_6

The connecting rod transformation formula is defined as follows:

$$^{i-1}T_i = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -d_i s\alpha_{i-1} \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & d_i c\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

There is a note that c represents $\cos$ and s represents $\sin$ in each formula in this paper.

According to the D-H parameters table and the connecting rod transformation formula, the coordinate transformation matrix of each coordinate system can be defined as follows:

$$^0T_1 = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ^1T_2 = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^2T_3 = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ -s\theta_3 & -c\theta_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ^3T_4 = \begin{bmatrix} c\theta_4 & -s\theta_4 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s\theta_4 & c\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^4T_5 = \begin{bmatrix} c\theta_5 & -s\theta_5 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ -s\theta_5 & -c\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ^5T_6 = \begin{bmatrix} c\theta_6 & -s\theta_6 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s\theta_6 & c\theta_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

The equation of the inverse kinematics solution is as follows:

$$^0T_6 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^0T_1(\theta_1)^1T_2(\theta_2)^2T_3(\theta_3)^3T_4(\theta_4)^4T_5(\theta_5)^5T_6(\theta_6) \quad (3)$$

By using the inverse matrix converter of both sides, reconstruct the equation (2) and equation (3), formula (4) can be derived

$$\begin{bmatrix} c_4c_5c_6+s_4s_6 & s_5s_6 & s_4c_5c_6+c_4s_6 & -s_6d_5 \\ -c_4c_5s_6+s_4c_6 & -s_5s_6 & -s_4c_5s_6+c_4s_6 & -c_6d_5 \\ s_5c_4 & -c_5 & s_4s_5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} n_x' & o_x' & a_x' & p_x' \\ n_y' & o_y' & a_y' & p_y' \\ n_z' & o_z' & a_z' & p_z' \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_1c_2c_3+s_1s_3 & -c_1c_2c_3+s_1s_3 & -c_1s_2 & -c_1s_2d_3 \\ s_1c_2c_3-c_1s_3 & -s_1c_2c_3-c_1s_3 & -s_1s_2 & -s_1s_2d_3 \\ -s_2c_3 & s_2c_3 & -c_2 & -c_2d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

According to formula (4), formula (5) can be conducted:

$$\begin{cases} -s_6 = -c_1s_2n_x'' - s_1s_2o_x'' - c_2a_x'' + p_x'' \\ -c_6 = -c_1s_2n_y'' - s_1s_2o_y'' - c_2a_y'' + p_y'' \\ 0 = -c_1s_2n_z'' - s_1s_2o_z'' - c_2a_z'' + p_z'' \end{cases} \quad (5)$$

In the formula (5): $n_x'' = n_x' d_3 / d_5, o_x'' = o_x' d_3 / d_5, a_x'' = a_x' d_3 / d_5, p_x'' = p_x' / d_5$, others just analogy.

By formula (5), all the θ angles are calculated so as to solve the inverse kinematics problem of arm.

2.2. The optimization of arm movement

2.2.1. The simplified equivalent transformation of arm movement

In order to simplify the movement analysis, the arm movement in three-dimensional space is equivalent to a two-dimensional space movement in a particular plane, and the specific method is as follows:

Three Degrees Of Freedom (DOF) of the shoulder joint can be regarded as the rotational movement around three mutually perpendicular axes in a coordinate system. It can be equivalent to a rotational movement around a shaft that is through the origin of the coordinate system.

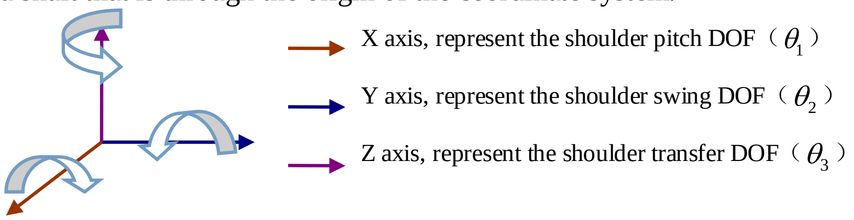

Figure 3. The reference coordinate system {A}

The rotary movement of three degrees of freedom of the shoulder joint uses the reference coordinate system {A}, as shown in Figure 3.

Let $\vec{k} = \begin{bmatrix} k_x & k_y & k_z \end{bmatrix}^T$ be a unit vector through the origin. If the rotation angle around $\vec{k}$ is θ, the rotation transformation matrix is $R(k,\theta)$. After the rotation transformation, the reference coordinate system {A} is transferred into coordinate system {B}. Then there are equations of the rotation transformation matrix as follows:

$${}_B^AR = R(k,\theta) = \begin{bmatrix} k_xk_x vers\theta + c\theta & k_yk_x vers\theta - k_zs\theta & k_zk_x vers\theta + k_ys\theta & 0 \\ k_xk_y vers\theta + k_zs\theta & k_yk_y vers\theta + c\theta & k_zk_y vers\theta - k_xs\theta & 0 \\ k_xk_z vers\theta - k_ys\theta & k_yk_z vers\theta + k_xs\theta & k_zk_z vers\theta + c\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

In the equation (6): $s\theta = \sin\theta, c\theta = \cos\theta, vers\theta = 1 - \cos\theta$;

$R(k,\theta)$ can also be obtained directly by rotation transformation, shown in equation (7):

$$
{}_{B}^{A}R = R(Z,\theta_3)R(Y,\theta_2)R(X,\theta_1)
= \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & 0 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\begin{bmatrix} \cos\theta_2 & 0 & \sin\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_2 & 0 & \cos\theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_1 & -\sin\theta_1 & 0 \\ 0 & \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}
$$

k_x, k_y, k_z and θ can be obtained by simultaneous equation (6) and (7).

2.2.2. Evaluation of arm movement based on improved Fitts's law

Fitts [11] proposed Index of Difficulty I_d and Index of Performance I_p based on one dimensional translational movement in the law, its definition is:

$$
\begin{cases} I_d^{\theta} = -\log_2(W/2A) \\ I_p^{\theta} = \dfrac{1}{t_m}\log_2(W/2A) \end{cases} \tag{8}
$$

In the formula(8): A is the range of movement, W is the width of object held by arm, t_m is the movement time.

Kondraske [12] further extended the Fitts's law to the angle movement, and proposed Index of Difficulty and Index of Performance of the angle movement, its definition is:

$$
\begin{cases} I_d^{\theta} = -\log_2(\theta_w/2\theta_A) \\ I_p^{\theta} = \dfrac{1}{t_m}\log_2(\theta_w/2\theta_A) \end{cases} \tag{9}
$$

In the formula (9): θ_A is the range of angle movement, θ_W is the object width of angle movement, t_m is the movement time.

The Fitts law based on one dimensional movement has great limitations. Therefore, an improved Fitts law is proposed to analyze and evaluate the two-dimensional movement.

The maximum range and the comfort range of movement about each joint DOF are shown in Table 2. The data in Table 2 are the statistical results obtained by sampling the large range of human movement.

Table 2. The range of movement for each degree of freedom

Joint degree of freedom	The maximum range of motion	The comfort range of motion
Shoulder pitch	0~180°	0~30°
Shoulder swing	-45°~135°	0~90°
Shoulder transfer	-135°~90°	-100°~0
Elbow pitch	0~142°	0~100°
Elbow transfer	-90°~90°	-45°~45°
Wrist pitch	-70°~90°	-25°~45°

When the arm is moving, a series of inverse solutions of θ_i are calculated. In order to evaluate the quality of solutions and select the most suitable set of values of θ, an evaluation criteria is proposed.

The simplified equivalent transformation of arm movement is established based on the parameter in Table2. The projection of the arm in the equivalent plane is shown in Figure4.

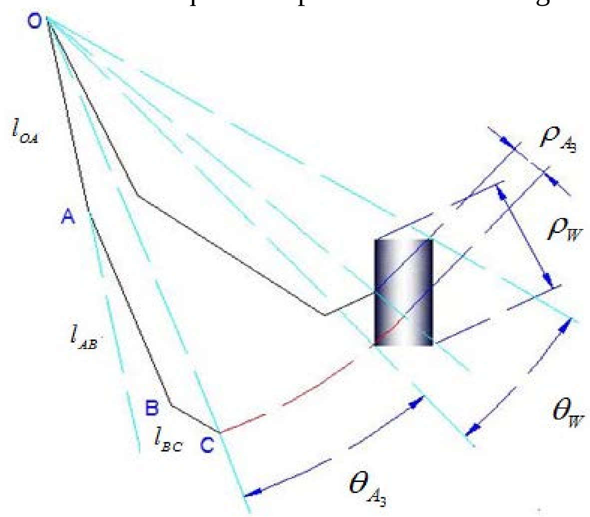

Figure 4. The projection of the arm in the equivalent plane

In Figure 4, O is the center point of the shoulder joint, A is the center point of the elbow joint, and B is the center point of the wrist joint, l_{OA} is the length of forearm, l_{AB} is the length of small arm, l_{BC} is the grasping length from the wrist joint center to the palm center; ρ_W is the maximum length of the object, θ_W is the maximum angle of the object in the equivalent plane, ρ_{A_3} is the motion amplitude of wrist, θ_{A_3} is the motion angle of wrist. In the equivalent plane, the evaluation function of each joint is obtained as follows:

The evaluation function of shoulder joint is defined as :

$$\begin{cases} I_{d_1}{}^{\theta} = -\log_2(\theta_w / 2\theta_{A_1}) \\ I_{p_1}{}^{\theta} = \dfrac{1}{t_m}\log_2(\theta_w / 2\theta_{A_1}) \end{cases} \tag{10}$$

The evaluation function of elbow joint is defined as:

$$\begin{cases} I_{d_2}{}^{\theta} = \log_2(\theta_w / 2\theta_{A_2}) \\ I_{p_2}{}^{\theta} = -\dfrac{1}{t_m}\log_2(\theta_w / 2\theta_{A_2}) \\ I_{d_2}{}^{\rho} = \log_2(\rho_w / 2\rho_{A_2}) \\ I_{p_2}{}^{\rho} = -\dfrac{1}{t_m}\log_2(\rho_w / 2\rho_{A_2}) \end{cases} \tag{11}$$

The evaluation function of wrist joints is defined as :

$$\begin{cases} I_{d_3}{}^{\theta} = -\log_2(\theta_w / 2\theta_{A_3}) \\ I_{p_3}{}^{\theta} = \dfrac{1}{t_m}\log_2(\theta_w / 2\theta_{A_3}) \\ I_{d_3}{}^{\rho} = -\log_2(\rho_w / 2\rho_{A_3}) \\ I_{p_3}{}^{\rho} = \dfrac{1}{t_m}\log_2(\rho_w / 2\rho_{A_3}) \end{cases} \tag{12}$$

in the equations (10) (11) (12), $I_{d_i}{}^{\rho}, I_{d_i}{}^{\theta}$ is the Index of Difficulty of each join, $I_{p_i}{}^{\rho}, I_{p_i}{}^{\theta}$ is the Index of Performance of each joint, ρ_{A_i}, θ_{A_i} is the range and angle of movement for each joint.

According to the evaluation function of each joint, the evaluation function of the whole arm movement can be defined as follows:

$$\begin{cases} I_d{}^{\rho} = \dfrac{I_{d_2}{}^{\rho} + I_{d_3}{}^{\rho}}{2} \\ I_p{}^{\rho} = \dfrac{I_{p_2}{}^{\rho} + I_{p_3}{}^{\rho}}{2} \\ I_d{}^{\theta} = \dfrac{I_{d_1}{}^{\theta} + I_{d_2}{}^{\theta} + I_{d_3}{}^{\theta}}{3} \\ I_p{}^{\theta} = \dfrac{I_{p_1}{}^{\theta} + I_{p_2}{}^{\theta} + I_{p_3}{}^{\theta}}{3} \end{cases} \tag{13}$$

According to the definition, the smaller $I_d{}^{\rho}, I_d{}^{\theta}$ is and the larger $I_p{}^{\rho}, I_p{}^{\theta}$ is, the higher the comfort degree of movement is. This criteria is used to select the optimal arm movement.

The minimum values of $I_d{}^{\rho}$ and $I_d{}^{\theta}$ are defined as $I_d{}^{\rho}{}_{\min}$ and $I_d{}^{\theta}{}_{\min}$; the maximum values of $I_p{}^{\rho}$ and $I_p{}^{\theta}$ are defined as $I_p{}^{\rho}{}_{\max}$ and $I_p{}^{\theta}{}_{\max}$.

The optimization goal λ of arm movement is defined as:

$$\lambda = \frac{\left(\dfrac{I_d{}^{\theta}{}_{\min}}{I_d{}^{\theta}} + \dfrac{I_d{}^{\rho}{}_{\min}}{I_d{}^{\rho}} + \dfrac{I_p{}^{\theta}}{I_p{}^{\theta}{}_{\max}} + \dfrac{I_p{}^{\rho}}{I_p{}^{\rho}{}_{\max}} \right)}{4} \tag{14}$$

According to the definition, the closer to 1 the value of λ is, the closer to the optimal solution the arm movement is.

3. Experiments and results

In order to verify the effectiveness of the arm movement optimization method, the operations in a specific station in assembly workshop are regarded as objects. Using the evaluation function of arm movement, the optimal operations in the specific station can be obtained respectively, and the results are verified in the simulation platform CATIA.

In the example, the simple contact movement in the sagittal plane is a selected as the experimental object, as shown in Figure 5. The object is moved from point A to point C.

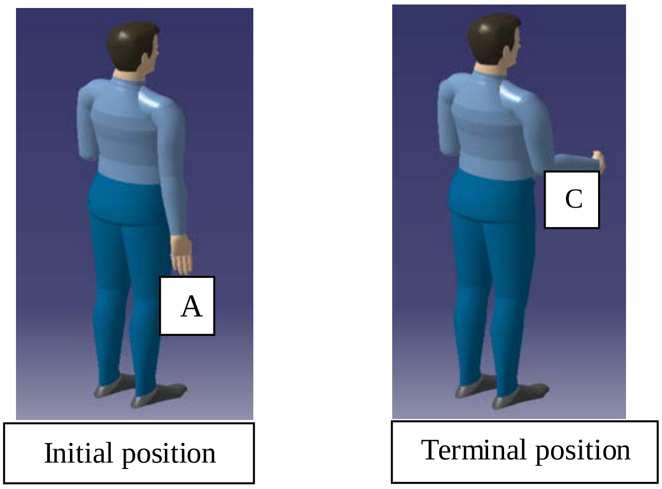

Figure 5. The contact action task

Three joint movement angles are focused on in this movement: shoulder swing angle θ_2, elbow pitch angle θ_4 and wrist pitch angle θ_6. When the movement is finished, the value of ρ_w is 12 , the value of θ_w is 15° and the value of t_m is 3.

(1) The joint angles of the six postures to achieve the task are shown in Table 3.

Table 3. The various postures of joint angle position within the range of body comfort

Posture	Shoulder swing θ_2	Elbow pitch θ_4	Wrist pitch θ_6
1	6°	78°	15°
2	9°	70°	36°
3	11°	64°	45°
4	13°	60°	62°
5	15°	56°	67°
6	17°	51°	71°

(2) The corresponding parameters of each posture projected in the equivalent two-dimensional plane are listed in Table 4:

Table 4. The parameters of each posture in the equivalent two-dimensional plane

Posture	movement angle of shoulder joint θ_{A_1}	motion range of elbow joint ρ_{A_2} (mm)	movement angle of elbow joint θ_{A_2}	motion range of wrist joint ρ_{A_3} (mm)	movement angle of wrist joint θ_{A_3}
1	6°	12.2	43°	15.5	52°
2	9°	10.2	41°	15.5	52°
3	11°	8.5	40°	15.5	52°
4	13°	7.5	39°	15.5	52°
5	15°	6.5	38.5°	15.5	52°
6	17°	5.5	38°	15.5	52°

(3)The parameters in Table 4 are put into the evaluation (10), (11), (12), (13) and (14), the evaluation results of the whole arm movement can be obtained, as shown in Table 5

Table 5. The evaluation results of the whole arm movement

Posture	I_d^{θ}	I_p^{θ}	I_d^{ρ}	I_p^{ρ}	λ
1	-0.01592	-0.00531	-1.51192	0.50400	1.00000
2	0.20197	-0.06732	-1.38277	0.46093	3.68490
3	0.31035	-0.10345	-1.25125	0.41709	5.38075
4	0.39674	-0.13225	-1.11157	0.37053	6.75029
5	0.47168	-0.15722	-1.05774	0.35258	7.93431
6	0.53248	-0.17749	-0.95650	0.31989	8.91025

In Table 5, the value of λ in posture 1 is 1. Therefore, the optimal solution is posture 1 according to the definition of evaluation function.

Take the first posture as an example, and the assessment result in CATIA is shown in Figure 6.

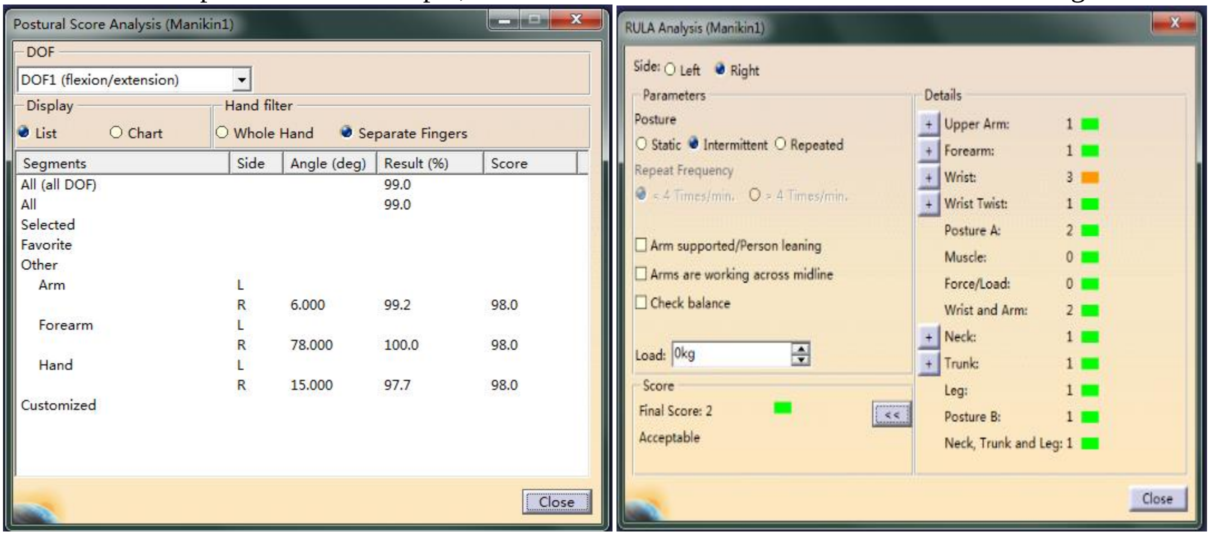

Figure 6. The assessment result of the first posture

The assessment result of six postures in CATIA is shown in Table 6.

Table 6. The assessment result of six postures in CATIA

Posture	Score of upper arm posture evaluation	Score of forearm posture evaluation	Score of wrist posture evaluation	Score of the whole posture evaluation
1	99.3	100	97.7	99.0
2	99.2	100	96.6	98.6
3	99.0	100	91.5	96.8
4	96.9	100	88.7	95.2
5	94.8	100	86.8	93.9
6	92.7	100	59.8	84.2

In Table 6, the assessment result of the first posture is the best because the first posture has the highest score, which is in accordance with the result obtained by the optimization method of arm movement.

4. Conclusions

An optimization algorithm of arm movement based on ergonomics is proposed to improve the work efficiency in the assembly workshop. The mathematical model of arm movement is established, and the evaluation function of arm movement is defined. The optimal movement posture is solved based on the evaluation function, and it is also verified by CATIA. In the future, combined with the mathematical model of human body movement, the optimization algorithm of human body movement based on ergonomics should be studied. The movement of operators can be optimized in the assembly workshop based on the algorithm to improve the work efficiency.

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