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Kinematics and workspace analysis of a modified portable exoskeleton arm

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Abstract. In order to solve the problems such as small workspace, complicated mechanical structure and motion interferences of traditional exoskeleton arm, a modified exoskeleton mechanism is proposed by optimizing the angles between the shoulder joint axes. In this paper, the model of traditional exoskeleton arm and the modified one are both built. And the kinematic theory of the two models is analysed and discussed. Furthermore, the Monte Carlo method is used to simulate the workspace of the mechanism with the help of the Matlab software. The simulation results show that the modified exoskeleton arm has larger workspace than the traditional one. So it can better meet the needs of more application scenarios.

1. Introduction

The exoskeleton arm is a bio-mechatronic device that integrates electronic, mechanical, biology, advanced control and other technologies. It has broad application prospects in the fields of modern military, industry, disaster relief, medical rehabilitation and so et al. So it has important theoretical and application value. The human upper-limb, including the shoulder, elbow and wrist joint, has a complex structure. The exoskeleton arm can work well when the degrees of freedom (DOFs) of the exoskeleton arm are equal to or greater than the ones of the upper-limb. For example, pneumatic exoskeleton auxiliary clothing (PAL) was developed by Japan Kanagawa institute of technology[1]. Military exoskeleton XOS2 was designed by American Raytheon Company[2]. 7DOF exoskeleton arm CADEN-7 was developed by Washington University[3]. The complexity of mechanism is greatly increased. The cost of mechanism is expensive. It limit the applicable field. So many scholars have proposed using a simplified kinematic model in order to reduce the complexity of the design. For example, two serial parallelograms were used to simulate the shoulder joint by WU et al[4]. In other projects NEF et al. presented an optimization method by shifting a rotation axis in the ball-and-socket joint[5]. A circular track is formed to simulate the spherical motion produced by the glenohumeral joint (GH joint). Lee et al. proposed a simplified model based on the physiological structure of the upper limb[6]. It uses the spatial separation of the exoskeleton and the upper limb to compensate for the inaccuracy of the model. Simplified kinematics model cause the following problem: a) the

simplified kinematics reduces the working space and limit the applicable field; b) Interference occurs between the branches and the arm.
The layout of this paper is organized as follows; The exoskeleton shoulder joint is analyzed and D-H model of traditional exoskeleton arm is established in section 2. In addition, the reasons for the small workspace of traditional exoskeleton arm are analyzed. So a modified portable exoskeleton arm is proposed by optimizing the angles between the shoulder joint axes. Compared with the traditional exoskeleton arm, the modified one has larger workspace. The forward kinematics of traditional exoskeleton arm and modified one are solved in section 3. The workspace of the two models is simulated in section 4. The simulation comparison and analysis of two models are also presented in this section. Finally the conclusion of this paper is shown in section 5.

2. Analysis of an exoskeleton shoulder joint

2.1. Analysis of a traditional exoskeleton shoulder joint
The most complicated part of the human upper limb is the shoulder joint. The traditional exoskeleton arms implement three mutually orthogonal series of joints which simulate the spherical motion produced by the GH joint. In order to analyze the traditional exoskeleton arm and modified one, a typical traditional exoskeleton D-H model and coordinate systems are established in this paper as shown in Figure 1.

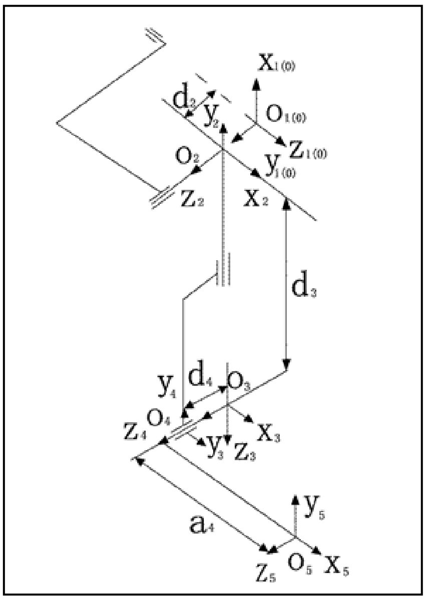


Figure 1. Traditional exoskeleton arm model
In order to meet the activities of daily living, the exoskeleton arm need achieve large working space. But it is difficult to reproduce the spherical motion in the traditional portable exoskeleton. The reason for this is that the design of the exoskeleton arm must be anthropomorphic. In addition, the three orthogonal joint axes will cause interference with the human arm or between the branches. Finally, the length of the arm should also be considered. Due to difference of individuals, everyone has different sizes of arms. That means the kinematic model must be able to adjust to suit different wearers. So the working space produced by the traditional portable exoskeleton arm can't assist people complete their most daily activities. Based on the previous work, a modified exoskeleton arm is proposed by optimizing the angles between the shoulder joint axes.

2.2. Design of a modified exoskeleton arm
As can be seen from the human anatomy, the shoulder joint is a ball-and-socket joint that can achieve abduction/adduction, flexion/extension, internal/external rotation. But three mutually perpendicular

joint axes hard to perform such movements. To perform this motion, a serial manipulator requires three series of rotating joints that intersect each other. In order to maximize the theoretical space of the end effector (regardless of the limitations of the physical joint), the following two inequalities must be met between the joint axes.

$$\frac{\pi}{2}-\theta_3 \le \theta_2 \le \frac{\pi}{2}+\theta_3 \tag{1}$$

$$\pi-\theta_2-\theta_3 \le \theta_1 \le \theta_2+\theta_3 \tag{2}$$

The angles are all from 0 to π. The relationship between the shoulder joint axis and the end effector is shown in Figure 2.

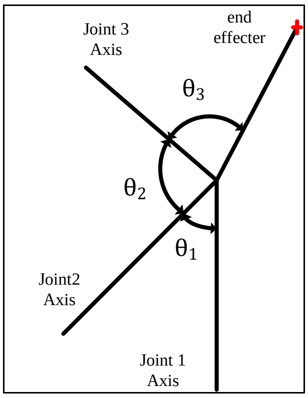


Figure 2. Relationship between shoulder joint axes and end effector[7]

To explain these two inequalities, the end effector and joint axis 3 are considered separately. The end effector is marked as a green dot, and the joint axis 3 is marked as a black line as shown in Fig 3(1). First rotating the end effector about the joint axis 3 will obtain a orange circle as shown in Fig 3(2).Then rotating the circle around the joint axis 2 produce an orange surface as shown in Fig 3(3).Rotating the orange surface around the joint axis 1 yields a complete sphere as shown in Fig 3(4). In order to ensure that workspace of the end effector is maximized, the orange surface must contain a complete large circle, and the joint axis 1 must intersect this circle. Inequality (1) describe the condition that the orange surface contains a complete large circle. Inequality (2) describe the condition under which the first joint axis intersects this circle.

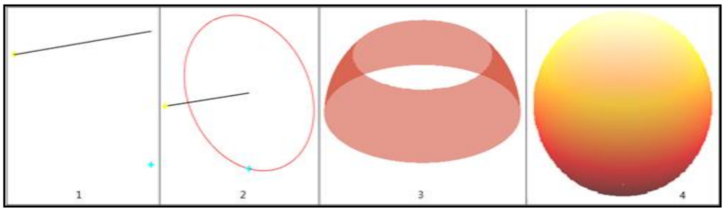


Figure 3. Step in determining workspace of three intersecting axis

The exact value of the angle selection between adjacent joint axes affects the position of the singular points in the workspace and the range of joint limits. Considering these factors, the modified exoskeleton arm is shown in Figure 4. Where the modified exoskeleton arm is worn on the 3D man model. The arm of the 3D model can swing freely like a normal person.

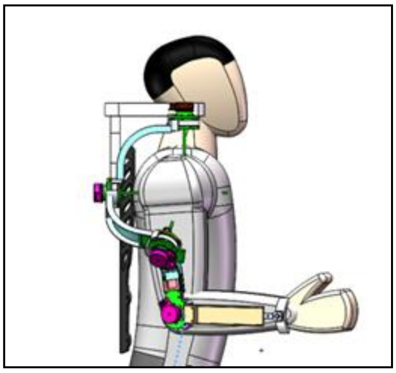


Figure 4. Modified exoskeleton arm of 3D model

3. Kinematics analysis of an exoskeleton arm

3.1. Forward kinematics analysis of a traditional exoskeleton arm

Due to the compact structure of the traditional exoskeleton arm and the small interval space between the branches and the arm, interferences may occur during the auxiliary human motion. It could cause serious injury for human arm or unable to reach the desire positions. So the joint angles should be restricted. The range limit of each joint is shown in Table 1

$$ {}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

Table 1. Joint limit of traditional exoskeleton arm

Joint Action	Joint Limit(degrees)	
	Min	Max
abduction/adduction	0	90
flexion/extension	-120	30
Internal/external rotation	45	90
flexion/extension of elbow	-90	30

The linkage coordinate systems were established on traditional exoskeleton model as shown in Figure 1. The D-H parameters are shown in Table 2

Table 2. D-H parameters of traditional exoskeleton arm

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0°	0	θ_1
2	0	90°	d_2	θ_2
3	0	90°	d_3	θ_3
4	0	-90°	d_4	θ_4
5	a_4	0°	0	θ_5

Substituting the parameters in the table 2 into the formula (3) can get the positive kinematics of the traditional exoskeleton arm.

$$ p_x^{'} = (c_1c_2c_3c_4 - s_1s_3s_4 - c_1c_2s_4)a_4 - c_1c_2s_3d_4 - s_1c_3d_4 + c_1s_2d_3 - s_1d_2 \tag{4} $$

$$ p_y^{'} = (s_1c_2c_3c_4 - s_1s_2s_4 + c_1s_3c_4)a_4 - s_1c_2s_3d_4 + c_1c_3d_4 + s_1s_2d_2 + c_1d_2 \tag{5} $$

$$ p_z^{'} = (-s_2c_3c_4 - c_2s_4)a_4 + s_2s_3d_4 + c_2d_3 \tag{6} $$

Where $s_i = \sin(i), \mathrm{c}_i = \cos(i)$

3.2. Forward kinematics analysis of a modified exoskeleton arm

The coordinate systems were established on the modlfied mechanism as shown in Figure 5. The amount of movement of the Y-axis is not represented in the D-H model, while the modified mechanism has a translational amount on the Y-axis. Therefore the translation and rotation transformation of coordinates should be used to solve the transformation matrix

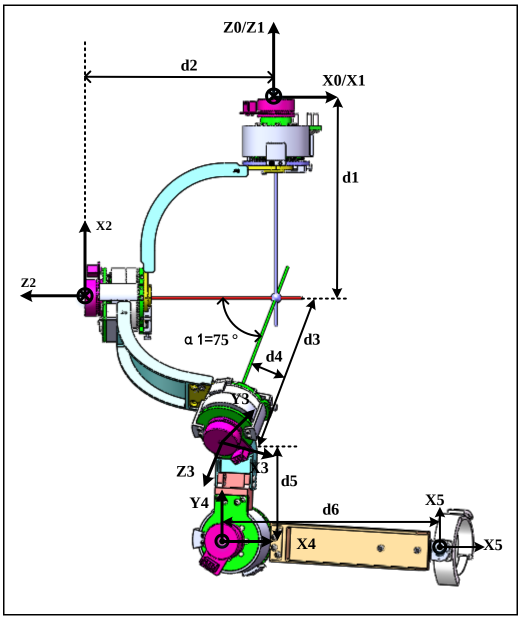


Figure 5. D-H linkage coordinate systems

$$
{}^0_1T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
{}^1_2T = \begin{bmatrix} c_2 & -s_2 & 0 & 0 \\ 0 & 0 & -1 & -a_2 \\ s_2 & c_2 & 0 & -a_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}
{}^2_3T = \begin{bmatrix} c_3 & -s_3 & 0 & 0 \\ a_9 s_3 & a_9 c_3 & -a_8 & -a_3 \\ a_8 s_3 & a_8 c_3 & a_9 & -a_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^3_4T = \begin{bmatrix} c_4 & -s_4 & 0 & 0 \\ a_{10} s_4 & a_{10} c_4 & a_{11} & -a_5 \\ -a_{11} s_4 & -a_{11} c_4 & a_{10} & a_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}
{}^4_5T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -a_7 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Where $a_1 = d_1, a_2 = d_2, a_3 = d_3 \sin 75^\circ, a_4 = d_2 - d_3 \cos 75^\circ$ $a_5 = d_4 + d_5 \cos 40^\circ, a_6 = d_6 \sin 40^\circ, a_7 = d_6$

$a_8 = \sin 75^\circ, a_9 = \cos 75^\circ, a_{10} = \cos 45^\circ, a_{11} = \sin 45^\circ$

After the coordinate transformation calculation, the kinematic equation of the exoskeleton is obtained

$$
{}^0_1T\,{}^1_2T\,{}^2_3T\,{}^3_4T\,{}^4_5T = {}^0_5T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}
$$

$$
\begin{aligned} p_x = {} & a_2 s_1 - a_4 s_1 + a_5(c_1 c_2 c_3 - a_8 c_3 s_1) + a_7(s_4(c_1 c_2 c_3 + a_8 s_3 s_1 - a_9 c_1 s_3 s_2) + a_{11} c_4 (a_9 s_1 + a_8 c_1 s_2) + a_{10} c_4 (c_1 c_2 s_3 - a_8 c_3 s_1)) \\ & + a_6(a_9 s_1 + a_8 c_1 s_2) + a_3 c_1 s_2 \end{aligned} \tag{8}
$$

$$p_y = a_4c_1 - a_2c_1 + a_5(a_8c_1c_3 + c_2s_1s_3 + a_9c_3s_1s_2) - a_7(s_4(a_8s_3c_1 - s_1c_2c_3 + a_9s_1s_3s_2) + a_{11}c_4(a_9c_1 - a_8s_1s_2) - a_{10}c_4(c_2s_1s_3 + a_8c_3c_1 + a_9c_3s_1s_2)) - a_6(a_9c_1 - a_8s_1s_2) + a_3s_1s_2 \tag{9}$$

$$p_z = a_7(s_4(c_3s_2 + a_9c_2s_3) + a_{10}c_4(s_2s_3 - a_9c_3c_2 - a_8a_{11}c_2c_4) - a_3c_2 - a_1 + a_5(s_2s_3 - a_9c_2c_3) - a_6a_8c_2 \tag{10}$$

4. Simulation and analysis of workspace

The workspace of the manipulator is an important kinematic indicator for measuring the performance of the robot[8]. It is also the basis for optimizing the structural and performance parameters. whether exoskeleton arm can accomplish the specific task can be judged by workspace. The workspace space of the exoskeleton refers to the set of points at which the reference point of the end of the exoskeleton can reach all discrete positions[9]. It commonly used methods including geometric drawing method, analytical method, numerical method, Monte Carlo method and so on[10]. Based on the analysis of kinematics, this paper simulates the working space of two exoskeleton models by Monte Carlo method. The two-dimensional and three-dimensional space maps obtained by Matlab simulation can visually observe the workspace of the mechanism.

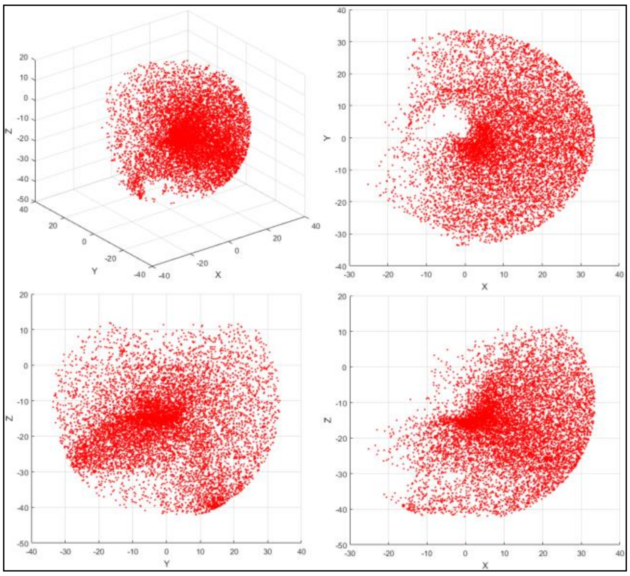


Figure 6. Workspace of a modified exoskeleton arm

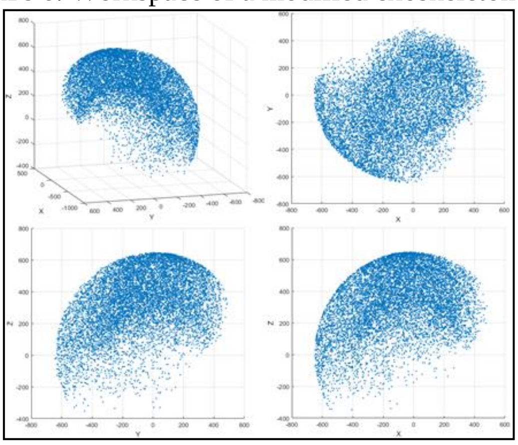
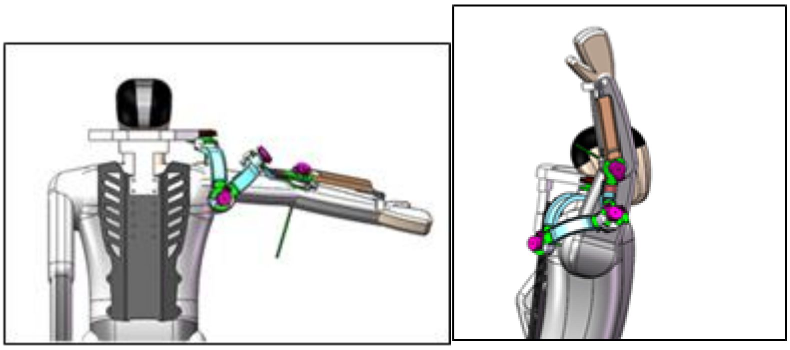


Figure 7. Workspace of a traditional exoskeleton arm

Based on theoretical analysis in section 2, the traditional exoskeleton has small workspace. The simulations of two models are shown in Figure 6 and 7. The working space of the modified exoskeleton arm is a notched sphere, while the workspace of the traditional one is a notched ellipsoid as shown in Figure 6 and 7. Compared with the ellipsoid, the sphere's workspace is obviously larger, which proves that the modified mechanism has a larger working space than the traditional one. In addition some of the extreme positions that modified exoskeleton arm can achieve compared with a traditional one is shown in Figure 8(a) and Figure 8(b). Traditional exoskeleton arm is difficult to reach these extreme positions due to compact structure or interferences. It also proves that the modified exoskeleton arm has larger working space than traditional one.



(a) (b)

Figure 8. Test of some extreme postures

5. Conclusion

Aiming at the shortcomings of the traditional exoskeleton arm, such as small working space and bulky structural, a modified portable exoskeleton mechanism is proposed. In addition, the kinematics of both exoskeleton models is analyzed in this paper. The Monte Carlo method was used to simulate the workspace of the mechanism with the help of the Matlab software. Compared with three mutually orthogonal series of joint, this configuration of exoskeleton arm has larger workspace. On the other hand, it can be seen from 3D model, the modified exoskeleton can reach some extreme positions. It also proves that the modified exoskeleton arm has larger workspace

Acknowledgements

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