Study on gravity calculation method of integration about an upper extremity exoskeleton and loads

Lin Feng, Qiuzhi Song*, Zhuo Qi and Xin Wang
School of Mechatronical Engineering, Beijing Institute of Technology, Beijing, 100081, China

*Corresponding author e-mail: qzhsong@bit.edu.com

Abstract. The gravity center of integration about the upper extremity exoskeleton and loads has a great impact on the balance control of the systemic exoskeleton system. In this paper, a new method is presented to calculate the gravity of the integration. First, build a model of the upper extremity exoskeleton by standard D-H method, analyze the model by kinematics and then obtain the function of the gravity center by analyzing the relationship between the structure parameters, joint angles and gravity center of the integration. Second, simulate each curve of the gravity center with lifting the load of 0, 10KG and 20KG under a specific trajectory determined by cycloid interpolation method. This paper lays a foundation to study on the balance control of the systemic exoskeleton system.

Keywords. Upper extremity exoskeleton, kinematics analysis, trajectory planning, gravity calculation.

1. Introduction
With the development of society and economy, robots appear inevitably. They enable humans to break through the limits of themselves and explore the unknown world. For humans, the upper limbs undertake most of the daily work of lifting or moving objects. Taking human as the main controller, it is positive to make a further move for enlarging the physiological ability and environmental adaptation of the upper limbs and expanding the field of human activities and work efficiency [1]. Recently, the exoskeleton system has become a new research hot point of the scientific field which includes robotics technology, electromechanical engineering, automatic control, bioengineering and artificial intelligence [2]. According to the different application requirement, the exoskeleton can be divided into rehabilitation exoskeleton and assisted exoskeleton.

As the above technology develops, the exoskeleton achieved great progress in recent year, such as a 7-DOF upper extremity rehabilitation exoskeleton CADEN-7 by Perry et al from American Washington University [3] [4], XOS-2 general exoskeleton by American Raytheon [5], a 6-DOF upper extremity exoskeleton with gravity compensation by Moubarak et al from INSA [6], a 6-DOF non-power upper extremity rehabilitation exoskeleton by Shanghai Jiao Tong University [7].

The assisted systemic exoskeleton system in this paper includes the upper extremity exoskeleton and the lower extremity exoskeleton. Although the upper extremity exoskeleton allowed for the lightweight design, the upper half of a person would bear too much when wearing the exoskeleton and lifting loads,
which would not only affect the power and driving mechanism performance of the lower extremity exoskeleton, but also cause the wearer to fall down out of balance [8]. For the rehabilitation exoskeleton which always works without loads, other authors usually use the gravity compensation in order to keep the wearer balance, however, it often requires a high quality control system [9]. But for the assisted exoskeleton, loads will have a great influence on the exoskeleton system when lifting or carrying them. If we only use the gravity compensation, the gravity of the loads are ignored.

However, the gravity center of integration about the upper extremity exoskeleton and loads has a great impact on the balance control of the systemic exoskeleton system which there are few studies in this aspect. Therefore, a new method is presented in this paper to calculate the gravity center of the integration. In this method, first, build a model of the upper extremity exoskeleton by standard D-H method and analyze the model by kinematics; second, calculate the function of the gravity center by analyzing the relationship between the structure parameters, joint angles and gravity center of the integration; third, simulate each curve of the gravity center with lifting the load of 0, 10KG and 20KG under a specific trajectory determined by cycloid interpolation method and verify the validity about the relationship of the gravity center and the structure parameters. This method lays a foundation to study on the balance control of the systemic exoskeleton system.

2.  Modeling and kinematics analysis of the upper extremity exoskeleton

2.1.  Structure design of the upper extremity exoskeleton

The main task of the upper extremity in this paper is lifting and carrying loads. On the premise of meeting the needs of a person’s daily life, the mechanism structure should be simplified, therefore, we choose three common degrees of freedom from the seven degrees of freedom of the upper limb. The shoulder joint has two degrees of freedom (flexion/extension and abduction/adduction), and the elbow joint has one degree of freedom (flexion/extension) [10]. The range of each joint is shown in Table 1 and the structure of the 3-DOF upper extremity exoskeleton is shown in Figure 1.

| Joint motion                                  | The range of a joint (degrees) |
|-----------------------------------------------|-------------------------------|
| The shoulder joint (flexion/extension)        | 170 ~ ~50                     |
| The shoulder joint (abduction/adduction)      | 180 ~ ~40                     |
| The elbow joint (flexion/extension)           | 150 ~ ~10                     |

![Figure 1](image1.png)  
**Figure 1.** The structure of the upper extremity exoskeleton.

![Figure 2](image2.png)  
**Figure 2.** The axes and planes of human.
In order to describe conveniently, the medical term will be used to express the axes and planes of the human body, as shown in Figure 2[11].

2.2. Exoskeleton modeling and kinematics analysis
Since the design structure of the exoskeleton is on the sagittal plane symmetry, the case of the left arm will be considered when modeling by standard D-H method. Because of 0-DOF of the wrist, actually the model is two links mechanism, and the kinematic structure of the prototype is shown in Figure 3[12]. Table 2 shows link parameters of this structure where the base coordinate system \{0\} is fixed to the shoulder joint; the coordinate system \{1\} is the flexion/extension coordinate system of the shoulder joint; the coordinate system \{2\} is the abduction/adduction coordinate system of the shoulder joint; the coordinate system \{3\} is the flexion/extension coordinate system of the elbow joint; the coordinate system \{4\} is fixed to the wrist joint.

\[
0 \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad 1 \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad 2 \begin{bmatrix} \cos \theta_2 & -\sin \theta_2 & 0 & 0 \\ \sin \theta_2 & \cos \theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\cos \theta_3 & \sin \theta_3 & 0 & 0 \end{bmatrix}, \quad 3 \begin{bmatrix} \cos \theta_3 & -\sin \theta_3 & l_1 & 0 \\ \sin \theta_3 & \cos \theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad 4 \begin{bmatrix} 1 & 0 & 0 & l_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.
\]

\(0^0T\)

\(1^1T\)

\(2^2T\)

\(3^3T\)

\(4^4T\)

Now \(4^4T\) is formed by matrix multiplication of the individual link matrices, that is,
3. Gravity calculation of integration about the upper extremity exoskeleton and loads

Take the procedure that the wearer’s arms are from sagging to lifting a load as an example, and the gravity center of the integration about the upper extremity exoskeleton and loads is calculated by considering the case of the left arm. That is: calculating the terminal trajectory by cycloid interpolation method and simulating the curve of the gravity center by MATLAB.

3.1. Analytical formula of gravity center

During this procedure, the initial and the end-time posture are given. Since the wrist joint has 0-DOF, it is assumed that the relative position between the load and the wrist joint in coordinate system \{4\} remains the same when lifting it. So the gravity center of the load at the initial moment can be measured. In this integration, the structure parameters of each part have been determined, therefore, it is known that: the weight of the upper arm is \(M_1\), the length is \(l_1\) and the gravity center in the coordinate system \{2\} is \(^0T_1 = ^0T_2T_1^T \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}\) (2)

Where

\[
\begin{align*}
 r_{11} &= -c_1(c_2s_1 + s_2c_3), & r_{12} &= c_1(s_2s_3 - c_2c_1), & r_{13} &= -s_1, \\
 r_{21} &= -s_1(c_2s_3 + s_2c_1), & r_{22} &= s_1(s_2s_3 - c_2c_1), & r_{23} &= c_1, \\
 r_{31} &= s_2s_3 - c_2c_1, & r_{32} &= c_2s_1 + s_2c_3, & r_{33} &= 0, \\
 p_x &= -l_2c_1(c_2s_3 + s_2c_1) - l_1c_2, & p_y &= -l_2s_1(c_2s_3 + s_2c_1) - l_1s_2, & p_z &= -l_1(c_2c_3 - s_2s_3) - l_2c_2
\end{align*}
\]

Where \(c_i = \cos \theta_i\) (i = 1, 3), \(s_i = \sin \theta_i\) (i = 1, 3), \(c_2 = \cos \theta'_2\) and \(s_2 = \sin \theta'_2\).

The gravity center of the upper arm is

\[ ^0G_1 = ^0T_2^2G_1 = ^0T_1T_2^2G_1 \] (3)

Where \(g_{1x} = -c_1s_2g'_{1x} - c_2c_1g'_{1y} - s_1s_2s_3 - c_1s_2g'_{1z} + c_2g'_{1x} + s_1s_2g'_{1z} = -c_1g'_{1x} - s_2g'_{1z} \)

The gravity center of the forearm is

\[ ^0G_2 = ^0T_3^3G_2 = ^0T_2T_3^2T_3^3G_2 \] (4)
\[ g_{2x} = r_{11}g_{3x} + r_{22}g_{3y} + l_{c3}r_{s2} , \quad g_{2y} = r_{21}g_{3x} + r_{22}g_{3y} + r_{33}r_{s2} - l_{c2}, \]
\[ g_{2z} = r_{12}g_{3y} + r_{22}g_{3y} + r_{13}r_{s2}, \]

And the gravity center of the load is
\[ 0G = 0_{T^4}G_3 = 0_{T^1T^2T^3T^4}G_3 \] (5)

Where \( g_{3x} = r_{11}g_{3x} + r_{12}g_{3y} + r_{13}r_{s2} + p_x, \quad g_{3y} = r_{21}g_{3x} + r_{22}g_{3y} + r_{33}r_{s2} + p_y, \]
\[ g_{3z} = r_{12}g_{3x} + r_{22}g_{3y} + r_{13}r_{s2} + p_z, \]

By combining the gravity centers of each part, it is known that the gravity center of the integration in coordinate system \( \{0\} \) is
\[ 0G = (g_x, g_y, g_z, 1)^T, \]
where
\[ g_x = \frac{M_1g_{1x} + M_2g_{2x} + M_3g_{3x}}{M_1 + M_2 + M_3}, \quad g_y = \frac{M_1g_{1y} + M_2g_{2y} + M_3g_{3y}}{M_1 + M_2 + M_3}, \]
\[ g_z = \frac{M_1g_{1z} + M_2g_{2z} + M_3g_{3z}}{M_1 + M_2 + M_3} \] (6)

In the Equation (6), \( g_x, g_y, \) and \( g_z \) are related to the structure parameters \( M_1, M_2, M_3, l_1, l_2 \) and joint angles \( \theta_1, \theta_2', \theta_3 \) where the structure parameters is known, but the joint angles is unknown. In actual work, the joint angles can be obtained by the angle sensors mounted on each joint of the upper extremity exoskeleton, then the gravity center of the integration can be determined.

### 3.2. Simulation analysis

#### 3.2.1. Motion trajectory determining

When simulating by MATLAB, it requires to obtain the joint motion trajectory. Then take the range of each joint as input values, the curve of the gravity center under a joint motion trajectory can be obtained according to the Equation (6).

However, we do not have a certain joint motion trajectory, so a specific joint motion trajectory is obtained by trajectory planning. In this paper, interpolation is used to plan a joint motion trajectory, so that the trajectory obtained is continuously differentiable to make sure that the robot moves smoothly.

For the point-to-point trajectories, the initial angular displacement \( \theta_0 \) and the end-time angular displacement \( \theta_f \) are required and the initial and the end-time angular velocity and acceleration are zero [13][14].

The cycloid interpolation method is simple to calculate, which can make sure that the motion trajectory is continuous and smooth, in the meanwhile, the initial and the end-time angular velocity and acceleration are zero when lifting the load in order to ensure steady motion.

For a step \( t_f \), the cycloid interpolation function of the joint motion trajectory is
\[ \theta(t) = (\theta_f - \theta_0) \left[ \frac{t}{t_f} - \frac{1}{2\pi} \sin \left( \frac{2\pi t}{t_f} \right) \right] + \theta_0 \] (7)
Therefore, the motion trajectory of each joint $\theta_1$, $\theta'_2$ and $\theta_3$ can be calculated by the cycloid interpolation method. During the procedure mentioned above, it can be measured that the shoulder flexion is 30 degrees, the abduction is 40 degrees and the elbow flexion is 90 degrees according to kinematic parameters of human. In other words, the range of $\theta_1$, $\theta'_2$ and $\theta_3$ is $(-\pi/6, 0)$, $(-2\pi/9, 0)$ and $(-\pi/2, 0)$.

Assuming the step is 2s, we can obtain the interpolation function of $\theta_1$, $\theta'_2$ and $\theta_3$ is

\[
\begin{align*}
\theta_1 &= -\frac{\pi}{6} \left[ \frac{t}{2} - \frac{1}{2\pi} \sin\left( \frac{\pi t}{2} \right) \right] \\
\theta'_2 &= -\frac{2\pi}{9} \left[ \frac{t}{2} - \frac{1}{2\pi} \sin\left( \frac{\pi t}{2} \right) \right] \\
\theta_3 &= -\frac{\pi}{2} \left[ \frac{t}{2} - \frac{1}{2\pi} \sin\left( \frac{\pi t}{2} \right) \right]
\end{align*}
\]

According to the Equation (8), the range of $\theta_1$, $\theta'_2$ and $\theta_3$ can be simulated by MATLAB, as shown in Figure 4.

According to Equation (2), the terminal trajectory in the coordinate system $\{0\}$ can be obtained under the joint motion trajectory given by Equation (8), as shown in Figure 5.

For simplicity, it is assumed that the load lift is homogeneous. For the procedure mentioned above, the wearer lift the load with two arms, therefore, the gravity center of the integration can be only considered in the sagittal plane. While the load is 0, 10KG and 20KG, the curves of gravity center in the coordinate system $\{0\}$ are respectively shown as Figure 6.
Figure 6. The curves of gravity center in the coordinate system {0}.

According to Figure 6, the gravity center of the integration changes continuously, in the meanwhile, is related to the posture of the exoskeleton as well as the distance between the load and the body when lifting a load, that is, when the upper extremity exoskeleton and the load approach the body, the gravity center approach the body and vice versa. Therefore, it is known that the heavier the load is, the greater impact on the distance the gravity center has.

4. Conclusion

Depend on the conclusion above, it is known that the gravity center of integration about the upper extremity exoskeleton and loads has a great impact on the balance control of the systemic exoskeleton system. Therefore, the loads cannot be ignored when dynamics analysis and balance controlling of the systemic exoskeleton system. It is important to study on the gravity center of the integration about the upper extremity exoskeleton and loads.

In this paper, a new method is presented to calculate the gravity of the integration. We build a model of the upper extremity exoskeleton by standard D-H method, analyze the model by kinematics and calculate the function of the gravity center by analyzing the relationship between the structure parameters, joint angles and gravity center of the integration. Then, we simulate each curve of the gravity center with lifting the load of 0, 10KG and 20KG under a specific trajectory determined by cycloid interpolation method and verify the validity about the relationship of the gravity center and the structure parameters. So that we can use the gravity calculated above when building the dynamics modeling of the lower extremity exoskeleton in order to keep the wearer balance afterwards.

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