

# Structural Design and Analysis of Knee Joint Rehabilitation Exoskeleton Robot

Junxi Jin<sup>1</sup>, Jie Wang<sup>2,\*</sup> and Hao Xie<sup>3</sup>

<sup>1</sup>School of International Education, Shenyang University, Shenyang 110000, China

<sup>2</sup>School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney 2052, Australia

<sup>3</sup>School of Mechanical Engineering, Nantong University, Nantong 226019, China

\* Corresponding Author Email: jie.wang12@student.unsw.edu.au

**Abstract.** This paper provides the design and optimization of a knee rehabilitation exoskeleton robot, focusing on mechanical structure, material selection, and motion mechanics analysis. First, it starts by identifying design requirements based on knee joint biomechanics. The design uses a tandem elastic actuator as the main power source and includes a crank guide rod mechanism to adjust the lengths of the thigh and calf segments. This helps reduce the peak force demand during actuation and improves the comfort of human-computer interaction and the degree of lightweight of the device. The study also analyzed the kinematic parameters of the knee joint to ensure that the exoskeleton can effectively support the needs of patients during rehabilitation training and limit the knee range of motion to a safe range through the mechanics. Furthermore, the paper compares the properties of three materials, titanium alloy, carbon fiber, and aluminum alloy, and discusses how to balance factors such as strength, weight, durability, and cost in exoskeleton design. The final design of the exoskeleton robot is not only suitable for rehabilitation training but also able to provide continuous power support for patients with permanent disabilities and effectively improve their quality of life.

**Keywords:** Knee exoskeleton, crank-guide mechanism, material selection, kinematic analysis, lightweight design.

## 1. Introduction

Exoskeleton robots are widely used in the field of rehabilitation as wearable devices that can cover specific parts of the body, prevent external shocks in advance, provide strong muscle strength and endurance, and be used to rehabilitate and assist patients, thus helping humans to accomplish various tasks [1-3]. With increasing global aging, the demand for rehabilitation is expected to increase significantly by 2050, especially as the physical functions of the elderly gradually deteriorate, and the demand for wearable robots for daily living assistance will also grow significantly [4]. Exoskeleton robots play an equally important role in rehabilitation and gait assistance for stroke patients. Because of the need of the application scenario, these devices need to be adapted to patient populations with different weights, heights, genders, and diseases, and their mechanical parameters, sensors, and hardware and software architectures must be flexible enough to be adapted to each individual patient [5].

Over the past two decades, the interest in this application-specific robotics has continued to rise as the demand for traditional rehabilitation systems continues to increase, as it is seen as a cost-effective solution. Rehabilitation with the aid of a robot allows for more repetitive movements than manual rehabilitation, thereby stimulating neuroplasticity in the brain and spinal cord through proprioceptive input generated by limb movements. This neuroplasticity is essential for restoring limb mobility in patients with some neuromuscular diseases [1]. The human knee plays an important role in activities such as standing and walking in daily life, but for many patients with knee injuries, being able to stand and walk normally has become very difficult. These patients are usually accompanied by symptoms such as muscle weakness, joint pain, paralysis, and gait disorders, which are mainly triggered by diseases such as stroke, spinal cord injury, poliomyelitis, trauma, and osteoarthritis [2], and these problems seriously affect their quality of life. For these symptoms, assistive lower limb

exoskeletons provide an effective treatment option. This exoskeleton robot is a wearable device designed to mimic the structure of the human lower limb, which can help patients with limited lower limb function due to disease or congenital disability to regain their walking ability and is also suitable for the training needs of the elderly and rehabilitation patients. In rehabilitation, the core goal is to restore as much motor function as possible to the patient, while in augmentation, the goal is to delay the onset of the most severe symptoms. In either case, kinematic and kinetic parameters must be considered in the robot control loop. Current state-of-the-art control strategies integrate the patient's intrinsic muscle strength as measured by electromyographic sensors

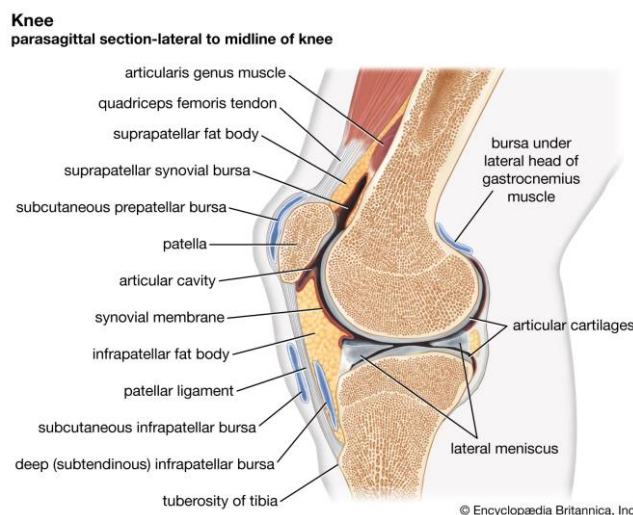
This article centers on the optimization of the knee rehabilitation exoskeleton robot's structural design. The research encompasses several topics, including mechanical design, material selection, and motion mechanics analysis. First, we had to adjust the exoskeleton's particular applicability to each patient's specific needs, as each person has a unique body shape and set of gait variables. To maintain or restore a certain mobility, the exoskeleton uses electrical impulses to monitor or estimate each patient's kinematic and kinetic data during the treatment. To ensure that each patient's therapy plan is tailored automatically, this data may be included into a real-time adaptive control architecture. We have also enhanced the lightweight design. This design feature facilitates patient mobility and ease of use, as well as making the device more economical for patients to acquire. It also makes it easier for the user to operate. Moreover, it may be used as an upgraded robot for people with multiple sclerosis or other chronic disabilities, providing the required power in the event that the patient becomes immobile.

## 2. Design and Analysis

### 2.1. Analysis of Human Body Structure and Parameters

#### 2.1.1. Structure analysis of lacquer joints

As shown in Figure 1, the knee joint consists of the femur, tibia, fibula, patella, meniscus, quadriceps, rectus femoris, medial collateral ligament, lateral collateral ligament, anterior cruciate ligament, and posterior cruciate ligament. The movement of the knee joint mainly relies on the contraction and extension of the relevant ligaments and tendons. Specifically, the extension motion of the knee joint combines the rollback motion characteristics of rotation and sliding, and the axis of rotation moves in response to changes in the angle of the knee joint. Therefore, any attempt to design a mechanical knee joint with a fixed axis of rotation would be difficult to fully mimic the natural motion of the human knee. In order to design a mechanical knee joint with a fixed axis of rotation as close as possible to the natural motion of the human body, the mechanism of motion of the knee joint must first be analyzed in depth [6].



**Figure. 1** Schematic diagram of the knee joint structure [7]

### 2.1.2. Analysis of human parameters

In order to better adjust the parameters involved in the design, it is very necessary to collect and analyze the movement parameters of the knee joint. This paper collects the angle range of movement of the knee joint front and rear flexion and extension and left and right rotation, as shown in Table 1.

**Table 1.** Range table of paint joint movement angle

The way of exercise	Range of motion angle
Inner spin/external spin	(-15°~-30°)~60°
Bending and stretching	(120°~160°)~0°

Wearability is one of the key factors that must be focused on in the design of knee exoskeletons. In order to ensure optimization of comfort and human-computer interaction, the design must be compatible with the anatomy of the human knee and the morphology of the legs. Therefore, accurate knowledge of the relevant dimensions of the human body is crucial for realizing the adaptation of exoskeleton devices to patients of different heights, and wearable devices with adjustable functions need to be designed based on this. For this purpose, we refer to the authoritative data source of Chinese Adult Human Body Dimensions and use it as the data basis for the design process. The key body dimensions of Chinese adult males and females are shown in Tables 2 and Table 3, providing key parameters for design optimization.

**Table 2.** The body size of men aged 18 to 60

percentage	1	5	10	50	90	95	99
height	1543	1583	1604	1678	1754	1775	1814
weight	44	48	50	59	71	75	83
Length of thighs	413	428	436	465	496	505	523
Length of calf	324	338	344	369	396	403	419

**Table 3.** The body size of women aged 18 to 60

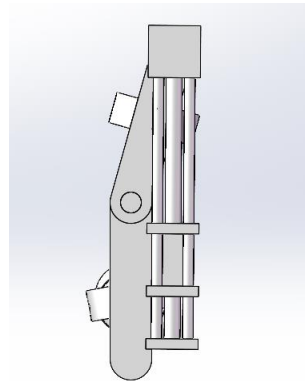
percentage	1	5	10	50	90	95	99
height	1449	1483	1503	1570	1640	1659	1679
weight	39	42	44	52	63	66	71
Length of thighs	387	402	410	438	467	476	494
Length of calf	300	313	313	344	357	370	390

## 2.2. Optimised Design of the Working Part of the Painted Joint Exoskeleton

### 2.2.1. Design scheme of the working part of the knee joint exoskeleton

An efficient and reliable mechanism configuration can significantly improve the safety and applicability of the device, thus better promoting the recovery of knee joint function and the assistance of human movement. Therefore, the design based on the adaptability of human-computer interaction should meet the following requirements: 1) Functionality: The primary goal of the mechanism design is to realize the basic function, i.e., to provide effective motion assistance for patients so that their gait is as close as possible to the normal walking state. 2) Portable and lightweight: the design of the mechanism should pursue simple structure, small volume, light weight, so as to facilitate carrying and operation, while reducing the manufacturing cost, so as to achieve a balance between functionality and economy. 3) Drive mode: compared with pneumatic drive, motor drive because of its low noise, flexible control, convenient operation and other advantages, become the design of the priority. Motor drive can reduce the inconvenience of the energy conversion process and enhance the practicality of the equipment. According to the above design requirements, combined with the movement characteristics and functional requirements of the knee joint of the human lower limb, this paper adopts an exoskeleton mechanism suitable for human knee gait in the support part (as shown

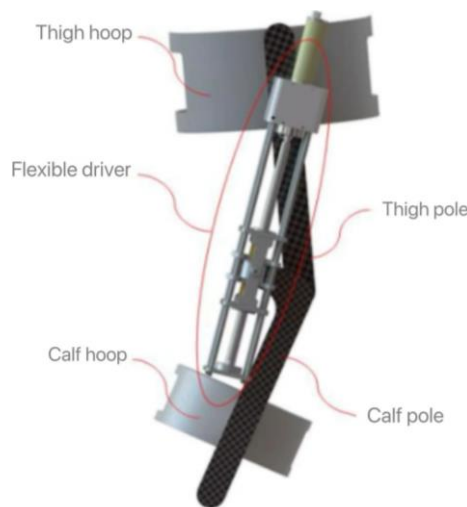
in Figure 2). It is mainly composed of thigh part, calf part, flexible driving device and various bolts, hinges and other connecting parts.



**Figure. 2.** The illustration of the exoskeleton standing (Photo credited: Original)

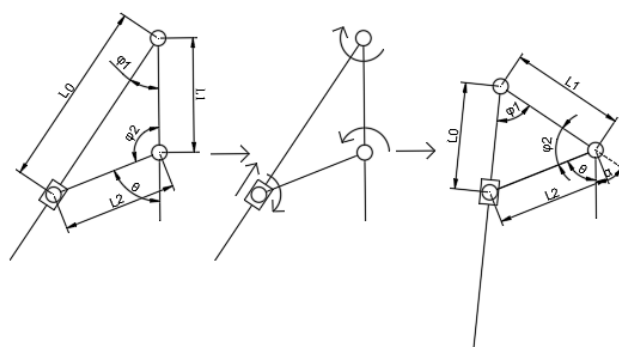
In this paper, the crank-guide mechanism is used as a kinematic prototype for mechanical structure design. There are three transmission vice and one moving vice. Since the human knee joint is most comfortable to stand and walk in a slightly curved state, the damage to the knee joint is also minimized, which is most conducive to the patient's rehabilitation training [8]. Therefore, in this design, we purposely added a protruding structure connecting the slider on the calf bar. As shown in Figure 3.

In the power section, this work chose a ball screw as the main power output element and added a linear compression spring set to form a tandem elastic actuator. This structure can realize efficient drive and flexible control at the same time, and it is lighter in weight and simpler in design compared with the traditional pneumatic mechanism.



**Figure. 3.** Schematic diagram of the flexible drive mechanism [9]

### 2.2.2. Kinematic analysis of the working part of the knee exoskeleton



**Figure 4.** Schematic diagram of kinematic analysis (Photo credited: Original)

Kinematic analysis of institutions: As shown in the Figure 4, the organization contains:

1) Two rotating joints (angle  $\Phi_1$  and  $\Phi_2$ ); 2) A sliding joint (Displace in the vertical direction)

The kinematic equations we know are:

$$d \sin \phi_1 = l_1 \sin \phi_2 \quad (1)$$

$$d \cos \phi_1 = l_2 - l_1 \cos \phi_2 \quad (2)$$

We can use these equations to calculate the joint angle  $\Phi_1$  and  $\Phi_2$ , and the position of the sliding joint  $d$ .

The formula of the unitary transformation matrix, For each joint  $i$ , the unitary transformation. Matrix  $T_i$  can be expressed as:

$$T_i = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 \cos \alpha_1 & \sin \theta_1 \sin \alpha_1 & a_i \cos \theta_1 \\ \sin \theta_1 & \cos \theta_1 \cos \alpha_1 & -\cos \theta_1 \sin \alpha_1 & a_i \sin \theta_1 \\ 0 & \sin \alpha_1 & \cos \alpha_1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Now we substitute the formula in the table. Transformation matrix  $T_i$  of joint 1.

1) For joint 1, there are the following parameters:  $\theta_1 = \Phi_1$ ,  $d_1 = d$ ,  $\alpha_1 = 0$ ,  $\alpha_1 = 0$

Substitute the formula to get:

$$T_1 = \begin{bmatrix} \cos \phi_1 & -\sin \phi_1 & 0 & 0 \\ \sin \phi_1 & \cos \phi_1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

2) Joint2 Trans formation Matrix  $T_2$ . For joint 2, there are the following parameters:  $\theta_2 = \Phi_2$ ,  $d_2 = 0$ ,  $\alpha_2 = 11$ ,  $\alpha_2 = 0$ . Substitute the formula to get:

$$T_2 = \begin{bmatrix} \cos \phi_2 & -\sin \phi_2 & 0 & l_1 \cos \phi_2 \\ \sin \phi_2 & \cos \phi_2 & 0 & l_1 \sin \phi_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

3) Joint 3 Transformation Matrix  $T_3$ . For joint 3, there are the following parameters:

- $\theta_3 = 0$  (Joint 3 does not rotate)
- $d_3 = 0$
- $\alpha_3 = 12$
- $\alpha_3 = \alpha$

Substitute the formula to get:

$$T_3 = \begin{bmatrix} 1 & 0 & 0 & l_2 \\ 0 & \cos \alpha & -\sin \alpha & 0 \\ 0 & \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

4) The matrix of unison change of the whole. The overall transformation matrix can be obtained by multiplying the transformation matrix of each joint:

$$T = T_1 \cdot T_2 \cdot T_3 \quad (7)$$

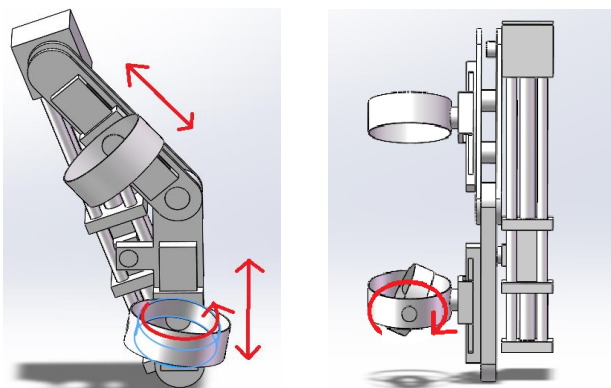
Multiply these matrices in order to obtain the final terminal actuator position.

### 2.3. The Design of the Knee Joint Exoskeleton Wear Part

As shown in Figure 5, the thigh frame mainly includes a thigh rod and an adjustable thigh hoop; the calf frame is composed of a calf rod and two vertically overlapping calf hoops. The two calf hoops are connected in a rotatable way, coupled with the rotational of the larger hoop and the calf rod, forming a range of movement of two degrees of freedom. , the wearer's calf can rotate in any direction forward,

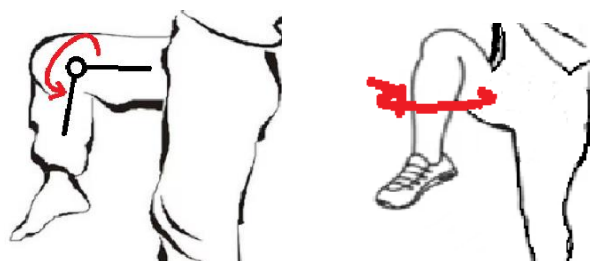
backward, left and right. The thigh rod and the calf rod are hinged by bearings to ensure the flexibility of joint movement.

In addition, the connection between the thigh rod and the thigh hoop, and the calf rod and the calf hoop adopts a moveable snap design. Through the snaps and knobs on both sides, the height of the thigh hoop and calf hoop can be freely adjusted to suit users of different heights, which is convenient for adjustment and wearing.



**Figure. 5** The schematic of how the wearing part moves (Photo credited: Original)

A significant advantage of this design is the addition of adjustable thigh hoops and calf hoops at the thighs and calves, including the adjustable size of hoops, adjustable relative position of hoops and rods, and adjustable relevant rotation positions between overlapping hoops. These adjustable devices can provide a higher degree of freedom, increase the comfort and adaptability of the equipment, and facilitate the patient to perform a variety of movements, such as walking, knee bending, stretching, etc. Especially at the knee, multi-way rotation can be realized as shown in Figure 6. In addition, the design of the hoop also takes into account ergonomics, which can fit the outline of the leg well, so as to improve the support effect and reduce the discomfort during use. During the research, we found that some existing exoskeletons adopted a small connecting rod structure in order to achieve the same effect in the design of the knee joint. Although it can also guarantee practicality, the structure is relatively complex and uses more materials. The structure we designed not only perfectly solves this problem, but also makes it simpler, saving production and maintenance costs and reducing the selling price.



**Figure. 6** Diagram of joint rotation (Photo credited: Original)

This design fully considers the needs of users of different postures, makes targeted improvements in terms of practicality and flexibility, and also takes into account the safety and stability of the equipment. Although this design is relatively simple, it can meet all the requirements in rehabilitation training and assisted walking scenarios. The range of movement of the knee joint after wearing is shown in Table 4.

**Table 4.** Table of rotation range of mechanism

Exercise status	Range of motion angle
Turn left and right	-20°~20°
Turn back and forth	0°~150°

## 2.4. Selection of Manufacturing Materials for the Knee Exoskeleton

From the perspective of biological structure, the lower limbs, as the main load-bearing parts of the human body, bear a huge burden in activities such as walking, running, etc. The pressure and impact of the lower limbs. Therefore, the lower limb exoskeleton needs to have sufficient strength and stability to ensure that it can effectively withstand the weight of the human body and the various impacts generated during the movement process.

This article carefully selected materials for knee joint exoskeletons. After comprehensive consideration of common materials such as aluminum alloy, titanium alloy, and carbon fiber on the market, carbon fiber is finally determined as the exoskeleton material.

From the weight perspective, exoskeletons often need to be worn by users for a long time. If the material is too heavy, it will bring a great burden to the wearer. Although aluminum alloy and titanium alloy are also lightweight metals, under the same strength requirements, carbon fiber is lighter in weight and can significantly reduce the overall weight of the exoskeleton.

In terms of strength, the strength of carbon fiber is much higher than that of aluminum alloy and titanium alloy. It can withstand greater external forces without being easily deformed or damaged. For exoskeletons, they need to provide stable support and protection for wearers in various complex usage environments. The high-strength characteristics of carbon fiber can better meet this need.

In terms of fatigue resistance, exoskeletons will continuously bear repeated loads and stress changes during long-term use. Carbon fiber has excellent fatigue resistance can maintain stable performance during long-term use and is not prone to fatigue damage. Aluminum alloy and titanium alloy may gradually develop fatigue cracks under repeated stress, which will affect the service life and safety of exoskeletons.

In terms of designability, carbon fiber can be customized according to different needs. By adjusting the arrangement and number of layers of fibers, specific requirements for the mechanical properties of exoskeletons at different parts can be met. For example, increase the number of fiber layers at parts that require higher strength, and adopt special fiber weaving methods at parts that require certain flexibility. In contrast, the shape and performance of aluminum alloy and titanium alloy are relatively fixed, and it is difficult to make such flexible design adjustments.

In addition, exoskeletons may be used in various harsh environments such as humidity, acids, and alkalis. Carbon fiber is not affected by these factors will not rust or corrode, and can maintain long-term stability. Although aluminum alloy and titanium alloy also have certain corrosion resistance, corrosion may still occur in some special environments.

## 3. Simulation Results

### 3.1. Main Results

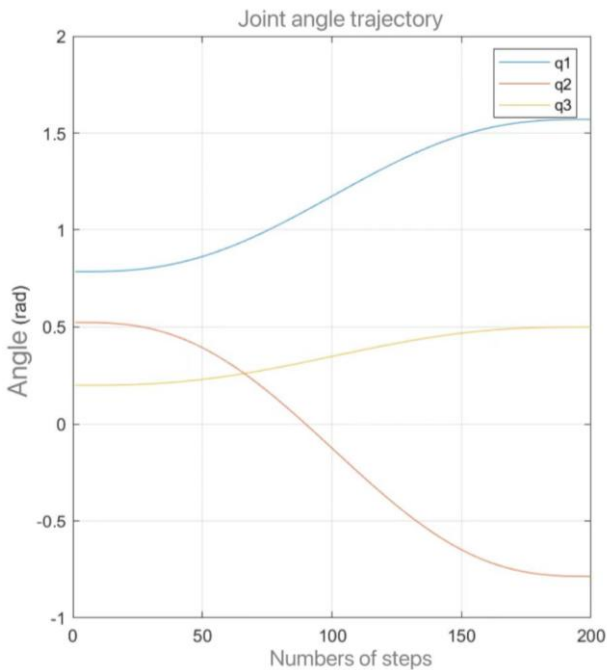
Figure 7 shows the joint angle trajectories for three different joints ( $q_1$ ,  $q_2$ ,  $q_3$ ) over the course of 200 steps. The angle of the joint changes nonlinearly. The angles of  $q_1$  and  $q_2$  joints are gradually increased or decreased from the initial position until the target position is reached.  $q_3$  represents the movement of the sliding joint, and its trajectory shows the change of sliding distance.

Figure 8 shows the joint velocity trajectories for three different joints ( $q_1$ ,  $q_2$ ,  $q_3$ ) over the course of 200 steps. It shows the changes in the speed of each joint during the whole trajectory planning process. The speed curve presents a smooth acceleration and deceleration process, indicating that the trajectory planning is buffered at the beginning and end of the speed to avoid sharp changes.

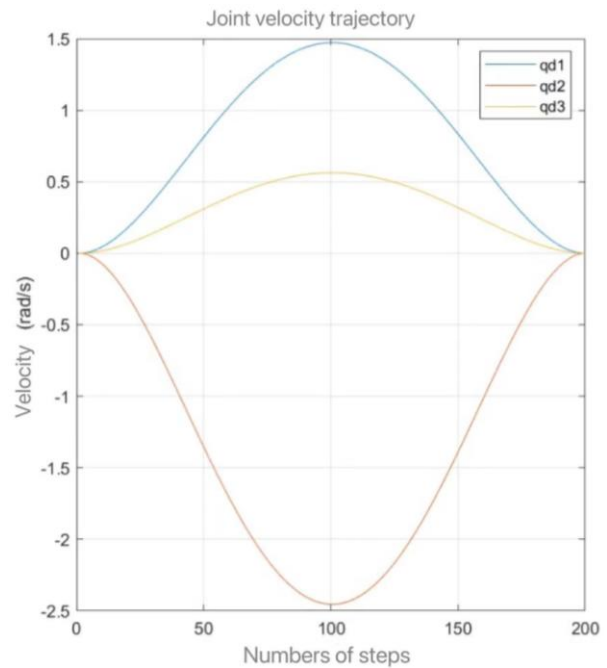
Figure 9 shows the joint acceleration trajectories for three different joints ( $q_1$ ,  $q_2$ ,  $q_3$ ) over the course of 200 steps. It shows the changes in the speed of each joint during the whole trajectory planning process. The speed curve presents a smooth acceleration and deceleration process, indicating that the trajectory planning is buffered at the beginning and end of the speed to avoid sharp changes. It also shows that the acceleration has distinct peaks and troughs in the middle during trajectory

generation, which corresponds to the smooth transition phase of the joint velocities. This acceleration profile is the key to achieving smooth motion.

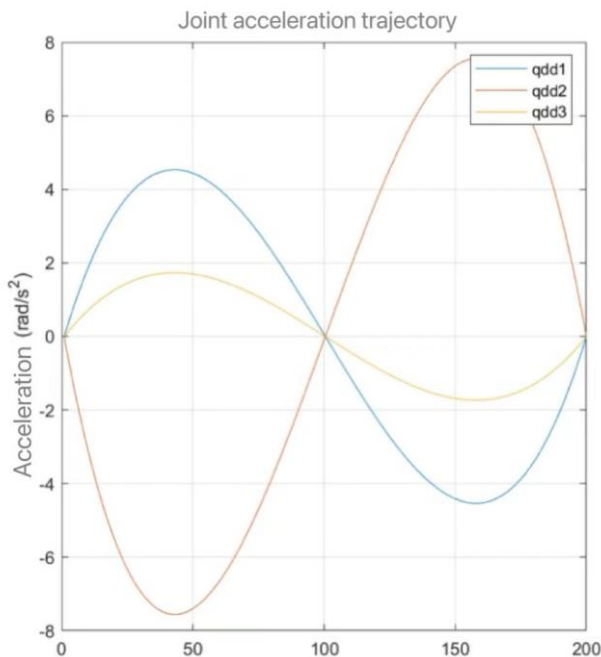
Figure 10 shows the 3D track of three different joints ( $q_1, q_2, q_3$ ) over the course of 200 steps. It can be seen from the figure that the movement of the end actuator on the Y and Z axes is more significant, while the change on the X axis is relatively small, which is in line with the movement characteristics of the robotic arm.



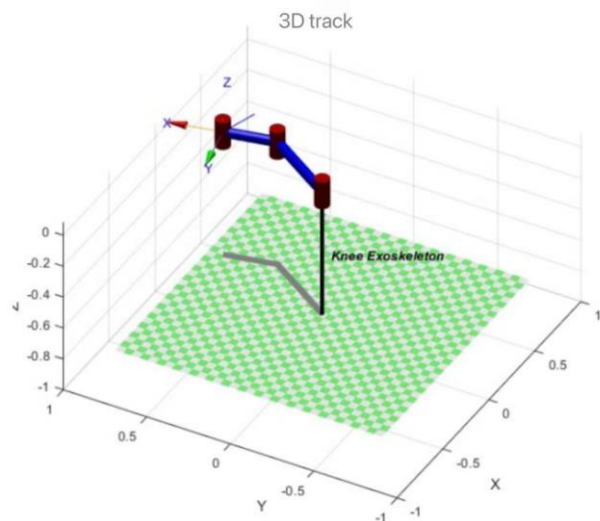
**Figure. 7** Joint angle trajectories  
 (Photo credited: Original)



**Figure. 8** Joint velocity trajectories  
 (Photo credited: Original)



**Figure. 9** Joint acceleration trajectories  
 (Photo credited: Original)



**Figure. 10** 3D track  
 (Photo credited: Original)

### 3.2. Discussion

This study also found a problem, a man-machine misalignment at the knee joint, during the study. It means the knee does not always coincide with the knee of the corresponding exoskeleton. When squatting and standing up, the opening and closing Angle of the human thigh and calf will be smaller than the Angle between the thigh bar and the calf bar stem of the exoskeleton because the wearing place cannot slide relative to each other. In order to solve this problem, the members of the team believe that it is necessary to measure the parameters of the human body and the exoskeleton respectively, and carry out calculation and analysis. Since both are 3R1P models, the classical model of man-machine misalignment in robotics can be used for reference.

### 4. Conclusion

This paper describes the design and development of a knee exoskeleton based on biomechanical analysis of the knee joint. A set of design requirements were first identified to guide the development of the exoskeleton, focusing on creating a compact, lightweight, reliable and comfortable device. A tandem elastic actuator was chosen as the power source to improve the comfort of the human-computer interaction. The structural design of the exoskeleton employs a crank-guide mechanism that is optimized by adjusting the relative lengths of the thigh and calf bars to better align with biomechanical data. This optimization also helps to reduce the peak force required for activation.

The exoskeleton is designed to have a working range suitable for human walking, while its mechanics limit the range of motion to safe limits, providing protection for the knee joint. This design approach not only ensures functionality and performance, but also addresses safety concerns by preventing excessive motion from causing injury to the user. In summary, the final design aims to improve the comfort, reliability and effectiveness of the knee assist device, making it ideal for users who require joint support during activities such as walking.

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