Motion simulation of Bionic Auxiliary Device for Ankle Rehabilitation based on small driving moment function

Hongpeng Li1, *, Chen Xia1, Feilong Li2, Jun Yin2, Xiaoliang Wang3, Jiacai Cheng4, Bingran Yang5, Penchant Dong5 and Enzhi Chen3

1Hydropower construction management center of Hydropower Management Division of Xinhua Hydropower CO., LTD, Zhengzhou, China
2Henan Xinhua Wuyue Pumped Storage Power Generation CO., LTD, Xinyang, China
3Zhongyuan Xinhua Water Conservancy and Hydropower Investment CO., LTD, Zhengzhou, China
4Xinjiang Xinhua Zangao Hydropower Development CO., LTD, Kashi, China
5Xinjiang Xinhua Yarkand River Hydropower CO., LTD, Kashi, China

*Corresponding author: liquntao@zxiat.org

Abstract. A kind of auxiliary device for ankle rehabilitation based on a ball pin vice is introduced in this paper first. The device has two degrees of freedom, while three-dimensional movement of the ankle can be achieved approximately. The modeling and simulation process of the ankle joint rehabilitation device are described in this paper. Motion simulation is preceded by using ADAMS for researching its dynamics and kinematics performance when the upper platform adopts small driving moment function to control the movement. The results are compared with the results of motion simulation driven by modified constant velocity function. The results show that the maximum driving torque of the motor driven by the small driving moment function is less than the maximum driving torque of the motor driven by the modified constant velocity function, which has a certain effect on saving energy consumption of the motor.

1. Introduction

Many scholars studied various ankle rehabilitation mechanisms. Lu Guangda [1] developed a 3-RSS/S parallel mechanism ankle rehabilitation robot and carried out relevant experimental research. Bi ZM [2] developed a rehabilitation robot adopting 3 DOF spherical parallel mechanism, which using three linear actuator. Wang liangwen [3] developed a kind of auxiliary device for ankle rehabilitation based on a ball pin vice which based on the researches for existing ankle rehabilitation mechanisms. Motion platform adopts different motion law will significantly change device movement characteristics [4, 5]. Compared with the centroid trajectory of robot controlled by small driving moment function and modified constant velocity function, the small driving moment function can reduce the energy consumption of the robot [6]. Based on the Gutman motion law, the trajectory planning method of modified trapezoid acceleration curve is used to plan the grasping and releasing trajectory of high-speed parallel manipulator, which makes the motion characteristics better [7]. Based on the 3-4-5 order polynomial motion law and aiming at the optimal energy consumption, the trajectory of a 4-DOF parallel robot is optimi
zed which can effectively reduce the output torque of each servo motor and improve the dynamic performance of the robot [8]. Tang Runzhi [9] used genetic algorithm to optimize the parameters of the motion curve to minimize the peak value of joint torque of the articulated manipulator. Zhang Wenxiang [10] used particle swarm optimization (PSO) algorithm to optimize the robot's movement time under the constraints of angular velocity and angular acceleration, so that the robot can run smoothly and keep the optimal running time.

The results show that the maximum driving torque of the motor driven by the small driving moment function is less than the maximum driving torque of the motor driven by the modified constant velocity function, which has a certain effect on saving energy consumption of the motor.

2. The Structural Description of the Device

The ankle joint involves dorsiflexion/plantar flexion, varus/valgus and adduction/abduction. Dorsiflexion/plantar flexion and varus/valgus are main motions which determine whether patients recover or not.

In this paper, we study the bionic auxiliary apparatus for ankle rehabilitation. The core of device is the clever combination of the sphere-pin pair. The device includes the upper platform, center sphere-pin, lower platform, drive of dorsiflexion/plantar flexion, drive of varus/valgus and control systems.

Motion for dorsiflexion/plantar flexion and varus/valgus are respectively driven by the servo motor, ball screw nut pair, spring, etc. The model is shown in Fig.1.

When the rehabilitation motion of dorsiflexion/plantar flexion of the ankle is needed to be realized, the motor I works. The motor I rotates a screw 4 to drive a slide block 6. The slide block 6 presses the spring 7. Lower platform 1 is used as a support. By using spring, the upper platform 8 is driven to deflect a definite angle along the direction of dorsiflexion/plantar flexion. The upper platform 8 can implement reciprocating movement. When foot joint is buckled on the upper platform 8, the dorsiflexion/plantar flexion motion of the foot is realized.

![Figure 1. The model of the device](image-url)
2.1. Motion Model of the Device

Assuming that the motor driving dorsiflexion/plantar flexion motion is motor I and the motor driving varus/valgus motion is motor II, there are five kinds of situations in the process of motion:

1. Motor I rotates, motor II does not rotate;
2. Motor II rotates, motor I does not rotate;
3. Motor I rotates first, motor II follows to rotate;
4. Motor II rotates first, motor I follows to rotate;
5. Motor I and motor II rotate at the same time.

As shown in Fig.2. \(B_1, B_2\) and \(B_3\) are initial positions, and \(B_1', B_2'\) and \(B_3'\) are positions after the upper platform moves. The rotation center \(O\) of center ball pin is used as origin to establish the fixed coordinate system \(x,e,z\), the coordinate system fixes on the lower platform.

In the motion simulation analysis, it is necessary to study the motion parameters of the platform and the driving torque of the motor.

2.2. Small drive moment function law

The dimensionless displacement curve of the small driving moment function [6] can be expressed as follows.

\[
S = \frac{1}{e-3}[e^T - e^{-T} - (e+1)T + e - 1]
\]  

(1)

The AV value of the motion law is small, which can make the system need less driving torque in theory. When \(T = T_i\) is given, the following equation is obtained by equation (1).

\[
S_i = \frac{1}{e-3}[e^{T_i} - e^{-T_i} - (e+1)T_i + e - 1]
\]  

(2)
2.3. Modified Constant Velocity Motion Law

The constant speed motion law is discontinuous on both ends. Harmonic transition curve is used at both ends, which can be used for medium and low speed and heavy load. Fig. 3 shows the acceleration law of modified isokinetic function.

![Figure 3. Modified Constant Velocity Motion Law](image)

The acceleration expression is as follows:

\[
A = \begin{cases} 
A_\text{s} \sin \frac{\pi T}{2T_s} & (0 \leq T \leq 1/16) \\
A_\text{s} \cos \frac{\pi(T - T_s)}{2(T_b - T_s)} & (1/16 \leq T \leq 1/4) \\
0 & (1/4 \leq T \leq 3/4) \\
-A_\text{s} \sin \frac{\pi(T - 1 + T_s)}{2(T_b - T_s)} & (3/4 \leq T \leq 15/16) \\
-A_\text{s} \cos \frac{\pi(T - 1 + T_s)}{2T_s} & (15/16 \leq T \leq 1)
\end{cases}
\]  (3)

3. Motion Simulation Based on ADAMS

Structural parameters of the device are shown as follows: \(a=150\text{mm}, b=150\text{mm}, l_1=704.1\text{mm}, l_3=12.7\text{mm}, l_4=691.4\text{mm}\); The load on the upper platform: 5kg; elasticity coefficient of the upper springs in the spring frame: \(K=5.5125\text{N/mm}\); elasticity coefficient of the following springs in the spring frame: \(K=7.4059\text{N/mm}\); the quality of the upper platform structure: \(m=6.537\text{kg}\), the mass of the moving box: \(m=1.269\text{kg}\).

After the input function of motor I is given, the mechanism is simulated by ADAMS software. The angular displacement of the upper platform, the angular velocity curve of the upper platform and the torque curve of the motor shaft can be obtained when the upper platform rotates around the Y-axis.

3.1. The simulation in the State of Springs Being Not at Solid Position

In this study, we only discusses that motor I rotates when the upper platform has a rated load and the spring is not pressed at solid position. The position function of the upper platform is small driving moment function and modified constant velocity motion. The upward movement time of the upper platform is set as 5S, and the downward movement time of the upper platform is set as 5S. The curves of angular displacement, angular velocity and angular acceleration of the upper platform around the Y-axis are shown as Figs 4-7.
The Upper Platform Moves Upward. The upper platform is driven by the small driving moment function, the output as shown in Figs 4-5.

When the upper platform moves upward or downward, the angular acceleration driven by the small driving moment function fluctuates at the end. The analysis of the reasons is related to the step size selected in the simulation, and the appropriate step size can be improved to some extent. When the upper platform moves up to the maximum position and downward to the minimum position, its spring is in compression state. The fluctuation of angular acceleration is related to the compression of spring.

On the whole, the angular acceleration value driven by small driving moment function is smaller than that driven by modified constant velocity function.

![Figure 4: The Angle Displacement, Angular Velocity and Angular Acceleration of Upper Platform around Y Axis](image4.jpg)

**Figure 4.** The Angle Displacement, Angular Velocity and Angular Acceleration of Upper Platform around Y Axis

![Figure 5: The Angle Displacement, Angular Velocity and Angular Acceleration of Upper Platform around Y Axis](image5.jpg)

**Figure 5.** The Angle Displacement, Angular Velocity and Angular Acceleration of Upper Platform around Y Axis
The Upper Platform Moves Down. The upper platform is driven by the modified constant velocity function, the output as shown in Figs 6-7.

![Figure 6](image1.png)

**Figure 6.** The Angle Displacement, Angular Velocity and Angular Acceleration of Upper Platform around Y Axis

![Figure 7](image2.png)

**Figure 7.** The Angle Displacement, Angular Velocity and Angular Acceleration of Upper Platform around Y Axis

3.2. **Driving Torque of Motor Shaft**

In order to study the driving torque of the motor, the rotation pair is added around the Z axis in the motor. The main weight of the upper platform is supported by the pillars of the second branch of the motor II and the large ball pin. Therefore, considering that the load distribution of the upper platform adopts uniform force distribution, the driving torque characteristics of the motor shaft of motor I and motor II are studied respectively. When using the small driving moment function and the modified constant velocity function to drive, the moving platform moves up to the maximum position and moves down to the minimum position from the balance position, the drive torque of the motor shaft can be gotten.
When driving with small driving moment function and modified constant velocity function, the corresponding driving torque is shown in Figs 8-9.

**Figure 8.** Torque for Upper Platform Upward Movement

**Figure 9.** Torque for Upper Platform Downward Movement.
When the upper platform moves up and down, the motor torque values of small driving moment function and modified constant speed function are basically the same at the beginning and the end. In contrast, the torque curve of the motor driven by small driving moment function is smoother.

3.3. Results analysis and comparison
The simulation results of these two kinds of driving functions are listed in Table 1. According to the analysis results, when the upper platform moves upward or downward, the maximum driving torque of motor I and motor II driven by small driving moment function is smaller than that of motor driven by modified constant velocity function.

| Project                  | Direction of movement | Maximum angular velocity(°/s) | Maximum angular acceleration(°/s²) | Motor I torque (N·mm) | Motor II torque (N·mm) |
|-------------------------|-----------------------|-------------------------------|-----------------------------------|-----------------------|-----------------------|
| Small driving moment    | upward                | 16.74                         | 6.92                              | 20.07                 | 33.61                 |
| Small driving moment    | downward              | -15.97                        | -21.16                            | 33.51                 | 47.70                 |
| Modified constant velocity | upward            | 9.48                          | -13.50                            | 22.14                 | 35.72                 |
| Modified constant velocity     | downward          | -8.92                         | -10.85                            | 35.25                 | 48.35                 |

4. Conclusion
In this paper, simulation analysis of the device is completed. The angular displacement, angular velocity and angular acceleration of the upper platform and the driving torque curve of motor spindle are obtained. The results show that the maximum driving torque of the motor driven by the small driving moment function is less than the maximum driving torque of the motor driven by the modified constant velocity function, which has a certain effect on saving energy consumption of the motor. The analysis results can provide reference for the structure design and motion control of similar bionic auxiliary device for ankle rehabilitation.

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