

# Ankle Active Rehabilitation Strategies Analysis Based on the Characteristics of Human and Robotic Integrated Biomechanics Simulation

Zhiwei Liao, Zongxin Lu, Chen Peng, Yang Li, Jun Zhang<sup>(✉)</sup>, and Ligang Yao<sup>(✉)</sup>

School of Mechanical Engineering and Automation, Fuzhou University,  
No. 2, Xueyuan Road, Fuzhou 350116, Fujian, China  
zhang\_jun@tju.edu.cn, ylgiao@fzu.edu.cn

**Abstract.** Ankle rehabilitation exercise therapy mainly includes passive, active, and resistance rehabilitations. Active rehabilitation exercise is highly important during ankle rehabilitation, how to combine the ankle and the rehabilitation robot has elicited considerable research attention. This paper proposed a combination strategy for the ankle and the rehabilitation robot based on a 3D modeling of the ankle and the robot developed individually based on simulation software (AnyBody). By integrating the 3D models of the human body and the robot, setting constraints between the pedal of the robot and the pelma of the human body and the degrees of freedom of the ankle is constrained as 3, a man-machine integration model for ankle active rehabilitation strategy analysis was established. Then, human muscle characteristics were established under the combination of different variables and the range of ankle motion were carried out by the human body active movement with ankle plantar/dorsal flexion motion, this further leads to strategies for ankle active rehabilitation. Finally, this paper designs the driving function for the robot based on Fourier function, and the force condition for the ankle movement during rehabilitation exercise was evaluated from the perspective of biomechanics. This study would provide a fundamental reference for the further formulation of active rehabilitation strategies and the control of rehabilitation robots.

**Keywords:** Ankle active rehabilitation · Biomechanics · Simulation · Rehabilitation strategies

## 1 Introduction

Ankle joint consists of many facet joints, bones, and tissues; the joint is one of the most complex joints in the human skeleton [1]. The ankle joint is the maximum load bearing joint of the human body and is easily injured, especially in athletes and the elderly [2]. Exercise therapy is one of the main methods of rehabilitation, and patients under the help of auxiliary equipment are required to complete the rehabilitation objective in a reasonable workspace. The exercise therapy of the ankle is a complex and lengthy process that includes three stages of early, mid-term, and late rehabilitation. Given the development of robot technology, the ankle rehabilitation robot became extensively investigated [3–13].

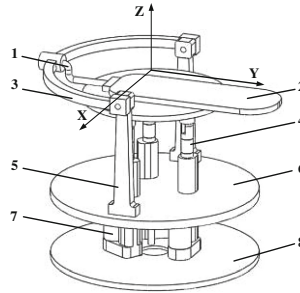
The development of biomechanics technology enabled research on ankle rehabilitation based on biomechanics to become one of the most attractive research fields. Warnica et al. [14, 15] investigated the effects of muscle activation and ankle stiffness on the amplitude and frequency of the postural sway and pointed out that the active contraction of muscles may play a different role in the balance control of ankle orthosis. Naito et al. [16] proposed a method to estimate muscle length parameters based on measured data. Benjamin et al. [17] investigated the effects of mechanical assistance on the biomechanical properties of the associated muscle system and completed the dynamic analysis of the biologically activated muscle and the skeleton stiffness. Cheung et al. [18] established a finite element model of ankle by using MRI images; the effects of the hardness and pressure of the pelma and the stress distribution of the bones are proposed. Zhang et al. [19–21] proposed a method for the prevention therapy and rehabilitation exercise of the ankle joint. Tang et al. [22] established the system and mechanical model of the 3D musculoskeletal system of the human body; the conversion between standard musculoskeletal system and individual musculoskeletal model is constructed. King et al. [23] analyzed the causation of ankle injury through the anatomy of the ankle joint and proved that ankle stability can be enhanced by increasing the muscle strength or ligament extension. Liu et al. [24] discussed the effects of force changes of the gastrocnemius muscle on the biomechanical mechanism of the pelma, thereby showing that the force changes of the gastrocnemius muscle significantly influence the pressure of the pelma and the stress of the plantar fascia.

This paper established an interaction model between the patients and a novel ankle rehabilitation robot and proposed a combination strategy for the ankle and the rehabilitation robot based on the 3D modeling of the ankle and the robot developed individually. Based on characteristics analysis of the human muscle under the combination of different variables and the range of ankle motion driven by the human body active movement with ankle plantar/dorsal flexion motion, strategies for the ankle active rehabilitation are proposed. Finally, the driving function for the robot based on the Fourier function is further provided, and the ankle movement during rehabilitation exercise is evaluated from the perspective of biomechanics.

## 2 Modeling of the Novel Robot and the Human Ankle

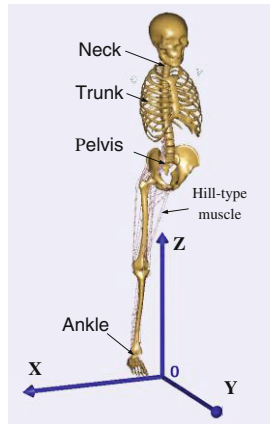
The 3D modeling of the novel ankle rehabilitation robot and the human ankle is fundamental for the analysis of the active rehabilitation strategies for the integrated robot and human system. To realize the three types of ankle movements for exercise therapy of ankle rehabilitation as well as the design of an ankle rehabilitation robot with the advantages of a simple structure, small size, light weight, easy to carry, and easy to move, a novel robot composed of series and parallel mechanisms is proposed, as shown in Fig. 1. The series part of the robot has one DOF, including moving platform, s-joint, rocker, bearing rod, and rotating platform, this part determines the abduction/adduction rehabilitating motions of the robot. The parallel part of the robot has two DOFs, including moving platform, three push-rods, and base platform, this part controls the plantar/dorsal flexion and the inversion/eversion rehabilitating motions of the robot. Three revolute pairs along the X-, Y-, and Z-axes

realized three types of ankle rehabilitation movements. The plantar/dorsal flexion motion is realized along the X-axis, whereas the inversion/eversion motion is realized along the Y-axis, and the abduction/adduction motion is realized along the Z-axis.



1. S-Joint 2. Moving platform 3. Rocker 4. Pushrod 5. Bearing rod 6. Rotating Platform 7. Stepper motor 8. Base platform

**Fig. 1.** Diagram of the ankle rehabilitation robot

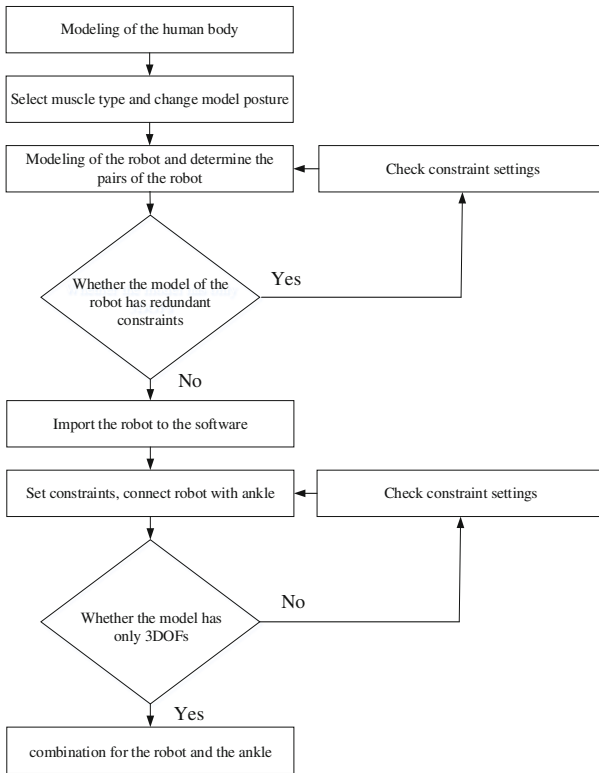


**Fig. 2.** Human body model

The 3D modeling of the human body is developed based on the AnyBody model library. Furthermore, the head, trunk, and right leg are preserved; the remaining parts of the human body are removed to increase the speed of calculation. In the human body model, the Hill-type muscle model is selected as real muscle because this model is more similar to the characteristics of a real human body. The model is constructed based on European standards, which recommend a default height of 180 cm and weight of 75 kg, as shown in Fig. 2.

### 3 Combination for the Robot and the Ankle Based on Biomechanics Simulation

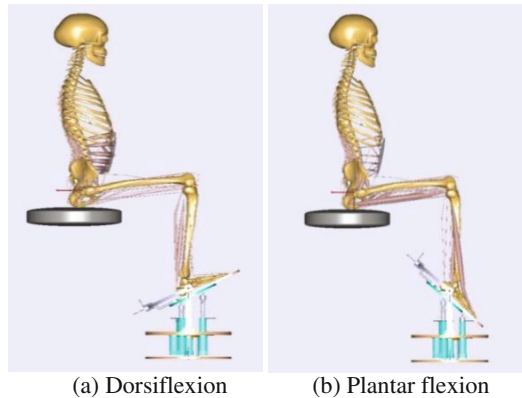
Based on the 3D modeling of the robot and the human ankle, a combination of the robot and the ankle is further proposed based on biomechanics simulation software. Before importing the robot to the simulation software, pairs of the robot must be determined to avoid redundant constraints. In addition, the constraints between the pedal of the robot and the pelma of the human body are set; the modeling of the human body with the robot is constrained to only three DOFs. Moreover, to simulate the rehabilitation process of patients in reality, the posture of the human body is adjusted, and the center point of the ankle joint is located on the axis of the Z. The specific process is shown in Fig. 3.



**Fig. 3.** Modeling and combination processes for the robot and the ankle

As shown in Fig. 3, the specific modeling and combination processes for the robot and the ankle are proposed. After the processes are completed, the pelvis of the human body, the three rotation directions of the trunk (Lateral Bending, Rotation, and Extension), and the rotation of the neck are fixed, and the combination modeling of the robot and the ankle only has three DOFs to achieve three types of movement. This paper

studies the plantar flexion and dorsiflexion movement of the ankle joint alone to analyze the active rehabilitation strategies of ankle rehabilitation, as shown in Fig. 4.



**Fig. 4.** Plantar flexion and dorsiflexion

In Fig. 4, the active rehabilitation process is the active contraction of the muscle to drive ankle movement because the moving platform is fixed with the human pelma; thus, the three pushrod movements are driven by the movement of the moving platform. The anterior and posterior crural muscles play major roles in the dorsiflexion and plantar flexion motions, respectively. The work in this section provides the basis for the investigation on the ankle active rehabilitation strategies.

## 4 Ankle Active Rehabilitation Strategies Analysis

Ankle rehabilitation after a series of ankle joint activity and strength training in early rehabilitation facilitates a certain recovery. In mid-term rehabilitation, active exercise is the main means of rehabilitation; fully active patients complete ankle movement by contracting the muscles around the ankle joint. In this section, the activity and power of related muscles and the passive traction of the muscle from different angles are analyzed. The maximum muscle activity is the percentage of the muscle strength, which performs the highest muscle activity. Relaxed muscles correspond to the highest percentage of 100%; percentages of more than 100% indicated no real meaning. The muscle power ( $P_{met}$ ) refers to a rough estimate of the total metabolic power consumed by all relevant muscles during active contraction in units of watts (W); the greater the power, the greater consumption per unit time. Muscle activity and muscle power in the rehabilitation process of patients cannot be increased sharply to avoid ankle pain. This paper analyzed the active rehabilitation strategies of patients based on the plantar and dorsal flexion motions. The purpose of the ankle active rehabilitation strategies in this section is to determine the appropriate rehabilitation range of patients.

### 4.1 Characteristics of the Muscles Under the Dorsiflexion of Active Rehabilitation

This section focuses on the maximum muscle activity and muscle power of the anterior crural muscles in different combinations of rotation angles and periods of motion because the anterior crural muscles play a major role in the dorsiflexion motion. In active ankle rehabilitation, patients perform exercise training by their own movement to drive the robot, and the force and torque of the model are provided by muscle contractions. On this basis, the motor of the robot “AnyKinEqFourierDriver” in the simulation software is turned off, and “Reaction.Type” is set to “off”. In recent years, researchers have studied the range of motion of the ankle joint [26–28]; the range of dorsiflexion is [10°, 60°], the interval is 10°, the range of the dorsiflexion period is [0, 10], and the interval is 2 s. Muscle activity and power are obtained.

As shown in Fig. 5(a), the period slightly affects muscle activity, if period  $T > 4$  and angle of motion is located in [10°, 20°] then the muscle activity increases with the increases of the angle. If angle of motion is located in [20°, 60°] and muscle activity is maintained at 40%, then minimal changes are observed. However, if period  $T < 4$  and angle  $\theta > 20^\circ$ , then muscle activity has significant changes. If period  $T < 2$  and angle  $\theta > 60^\circ$ , then muscle activity is close to 100%. As shown in Fig. 5(b), the period and the angle has minimal effects on muscle activity, if period  $T > 6$ , but if period  $T < 4$  and angle  $\theta > 20^\circ$ , then the muscle power has a sharp increase with the decrease of the period and the increase of the angle. Based on the above, this paper shortens the range of the angle in to [20°, 40°], and the interval is 1° to analyze the relationship among muscle activity, angle, and period of the movement (Fig. 6).

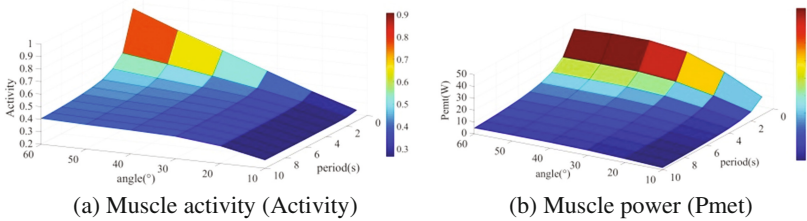


Fig. 5. Active dorsiflexion motion

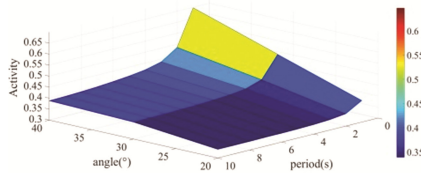


Fig. 6. Active dorsiflexion motion with 20°–40° maximum muscle activity

As shown in Fig. 6, if period  $T > 6$  and angle  $\theta < 30^\circ$ , then muscle activity increases with the increases in the angle; if period  $T < 6$ , muscle activity showed an increasing trend. The faster the active dorsiflexion, the greater the muscle consumption and the

influence of angle change on muscle power is relatively small, if angle  $\theta > 30^\circ$  and period  $T > 6$ , then the period and the angle has minimal effects on muscle activity. Continuing to increase the angle has no real meaning on the effect of the muscle activity. Based on above, the maximum angle of the active dorsiflexion motion can be selected at  $30^\circ$ , and the period of the motion not less than 6 s is appropriated.

## 4.2 Characteristics of the Muscles Under the Plantar Flexion of Active Rehabilitation

Similar to the previous section, this section focuses on the maximum muscle activity and the muscle power of the posterior crural muscles in different combinations of rotation angles and periods of motion. The range of the plantar flexion is  $-60^\circ$ — $10^\circ$ , the interval is  $10^\circ$ , the range of the plantar flexion period is 2 s–10 s, and the interval is 1 s. Muscle activity and power are obtained (Fig. 7).

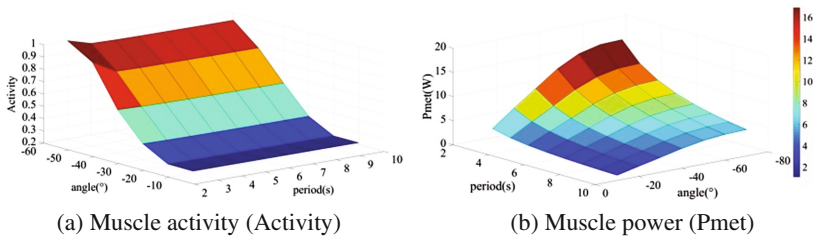
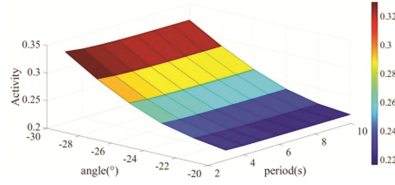


Fig. 7. Active plantar flexion motion

As shown in Fig. 7(a), period slightly affects muscle activity, and if period  $T > 4$ , then period has minimal effect on muscle activity. However, the angle of motion has considerable effect on muscle activity. If the angle of plantar flexion motion is located in  $-20^\circ$ — $-10^\circ$ , the muscle activity shows minimal changes and is maintained at 20%. However, if the angle is located in  $-60^\circ$ — $-20^\circ$ , the muscle activity has significant changes. Furthermore, if the angle reaches  $60^\circ$  and period  $T < 3$ , then muscle activity is close to 100%. As shown in Fig. 7(b), the period and angle affect muscle power, especially if the period is located in 3 s–6 s and the angle is located in  $-60^\circ$ — $-20^\circ$ . Muscle power increases sharply with the decreases of the period and the increases of the angle.

Based on the abovementioned discussion, this paper shortens the range of the angle by  $-30^\circ$ — $-20^\circ$  with an interval of 1 s to analyze the relationship among muscle activity, angle, and period of the movement (Fig. 8).

As shown in Fig. 8, if the angle is located in  $-20^\circ$ — $-24^\circ$ , then muscle activity increases slowly with the increases in the angle. If the angle is located in  $-24^\circ$ — $-30^\circ$ , then muscle activity increases more rapidly, but muscle activity has slight decreases as period increases. Thus, the period has a minimal effect on muscle activity during the motion of plantar flexion. Based on the above, the maximum angle of the active plantar flexion motion can be selected at  $24^\circ$ , and the period of the motion is selected the same as the dorsiflexion motion, in which not less than 6 s is appropriate.



**Fig. 8.** Active plantar flexion motion at  $30^\circ$ — $20^\circ$  maximum muscle activity of the posterior crural muscles

## 5 Driving Function Design and Rehabilitation Exercise Evaluation

In this section, the three types of ankle motion are realized based on the parameters obtained from the simulation of the active motion and the driving function of the rehabilitation mechanism designed by the rehabilitation strategies. Moreover, by measuring the active muscle contraction force of the anterior and posterior crural muscles in the entire process, the muscle contraction force of each part of the patients in the active rehabilitation process is obtained. The main muscle that influences the active rehabilitation of the patients' ankle can then be obtained.

The change of the angle in the ankle's plantar and dorsal flexion is similar to the sine curve. AnyBody provides the drive "AnyKinEqFourierDriver" with a reciprocating stroke. The drive that used Fourier expansion as the driving function has the following form:

$$\theta(t) = \sum_{i=1}^n A_i \sin(\omega_i t + B_i), i = 1, 2, 3, \dots, n, \quad (1)$$

where A and B are the Fourier coefficient, and  $\omega_i$  is the angular velocity, which can be expressed as

$$\omega_i = (i - 1)2\pi f, \quad (2)$$

where f is the frequency, and the unit is Hz. In Eqs. (1) and (2), by taking n equal to 2, we obtain

$$\theta(t) = A_1 \sin B_1 + A_2 \sin(2\pi f + B_2) \quad (3)$$

The sine functions with angles that vary with time can be used to obtain different driving functions with different amplitude, phase angle, and frequency by putting different A, B and f into equations.

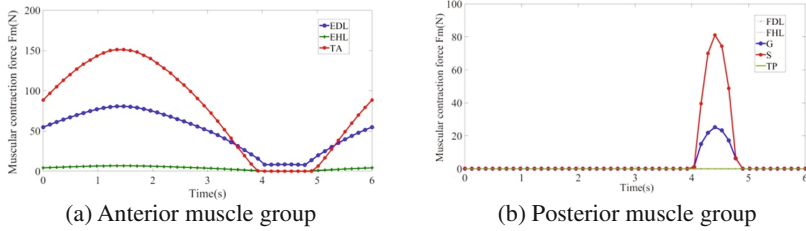
Based on the parameters of dorsiflexion and plantar flexion, we can obtain that the maximum angle of dorsiflexion is  $30^\circ$  and the maximum angle of plantar flexion is  $24^\circ$  and that the maximal muscle activity has a significant change in the increased speed. Therefore, the angles of dorsiflexion and plantar flexion are set as  $30^\circ$  and  $24^\circ$ , respectively, and the period is 6 s. Afterwards, simulating the motion of ankle in these settings and obtaining the driving function become simple, as shown below.



$$\theta(t) = \frac{3\pi}{20} \sin\left(\frac{\pi}{3}t - 0.035\pi\right) + \frac{\pi}{60}, \quad (4)$$

where  $A_1 = \frac{\pi}{60}$ ,  $A_2 = \frac{3\pi}{20}$ ,  $B_1 = \frac{\pi}{2}$ ,  $B_2 = -0.035\pi$ ,  $T = 6$ .

We input A, B, and T to the drive “AnyKinEqFourierDriver” and then add to the hinge Z. Thus, the rehabilitation robot can complete the plantar and dorsal flexion motions as shown in Eq. (4). The active contraction forces of the anterior and posterior crural muscles are obtained in a period (Fig. 7).



The anterior crural muscles: EDL-Extensor digitorum longus, EHL-Extensor hallucis longus, TA-Tibialis anterior.

The posterior crural muscles: FDL-Flexor digitorum longus, FHL-Flexor hallucis longus, G-Gastrocnemius, S-Soleus, TP-Tibialis posterior.

**Fig. 9.** Active contraction force  $F_m$  of the anterior and posterior crural muscles

As shown in Fig. 9, based on the drive function, the first half of the period is the active dorsiflexion motion of the patients, and the second half is the active plantar flexion motion of the patients. As shown in Fig. 9(a), the anterior crural muscles are important in active contraction when the patients are in active dorsiflexion motion. During dorsiflexion motion, given the increasing of the dorsiflexion angle, the active contraction force  $F_m$  of each muscle is also increased, and it gradually decreased during the recovery of the dorsiflexion motion. Among them, the TA and EDL play major roles in the anterior crural muscles, and the maximum muscle contraction forces reached 150 and 80 N, respectively. In addition, the TA also has a minimal inference of the movement, but this is not evident. As shown in Fig. 9(b), the posterior crural muscles are important in active contraction when the patients are in active plantar flexion motion. During the plantar flexion motion process, only S and G play major roles in the posterior crural muscles; the remaining muscles have minimal influences. Given the increasing plantar flexion angle, the active contraction force  $F_m$  of S and G is also increased and gradually decreased during the recovery of the plantar flexion motion. Among them, S play a significant role in the plantar flexion motion, and the maximum muscle contraction force reached 82 N. Furthermore, G has slight inference of the movement, and the maximum muscle contraction force reached 23 N.

## 6 Conclusions

In this paper, the muscle activity and power of the related muscles during the active rehabilitation of the ankle are analyzed based on the novel ankle rehabilitation robot and its analysis software AnyBody. By analyzing the parameters such as the periods and angles that occur during sharp movements, the limit positions of patients during active ankle rehabilitation are determined; this determination guides the design of active rehabilitation strategies for patients in this period. This paper examines the plantar and dorsal flexion of the ankle rehabilitation exercise of patients. The limit positions of the ankle in the process of the plantar and dorsal flexion are obtained. Based on biomechanical simulation, the maximum angle of dorsiflexion is  $30^\circ$ , and the maximum angle of plantar flexion is  $24^\circ$ . Therefore, the active rehabilitation strategies for patients in the period are designed. Based on the new rehabilitation strategies, the driving functions of ankle rehabilitation robot are proposed to drive the ankle joints and the muscles that play major roles in the process of plantar and dorsiflexion are then obtained through the analysis of active contraction force during the motion. This research benefits the formulation of active rehabilitation strategies. The data obtained from the simulation can effectively provide physicians with the recovery of patients. The feedback information of the new rehabilitation strategies are obtained in time, thereby making the ankle rehabilitation of patients more scientific and effective. This strategy effectively avoided the possibility of patients' injury during an ankle active rehabilitation exercise.

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