A New Type of Ankle-Foot Rehabilitation Robot Based on Muscle Motor Characteristics

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ABSTRACT
Ankle injury and dysfunction are always accompanied by abnormal peripheral tissues. In order to achieve a more comprehensive rehabilitation training, this article firstly studies the movement characteristics of the surrounding muscles of the ankle-foot. The human musculoskeletal model in OpenSim is used for human exercise experiment. And the relationship between different muscles around the ankle-foot and the direction of the ankle-foot movement are measured respectively, so as to formulate ankle-foot static/dynamic rehabilitation strategies related to the auxiliary training of the ankle-foot muscle. In order to implement the established rehabilitation exercise strategy and to reduce the control difficulty of rehabilitation robot, a new type of decoupling series-parallel mechanism with three rotations and one movement is proposed. After analyzing the degree of freedom and the positive kinematics solution, it is proved that it is completely decoupled in kinematics, can realize the independence of motion control, and there is no singular space. Then, under the premise of meeting the space required for the implementation of the rehabilitation strategy, the proposed new ankle-foot rehabilitation robot is optimized in terms of structure and component size, which improves its space utilization and optimizes the overall mechanical performance. Finally, the dynamic simulation experiment is carried out with the dynamic rehabilitation strategy as the goal, which proves that the robot can realize the normal gait simulation movement in sitting posture, and the motion control of the robot is independent of each other and shows good dynamic performance. Through investigation, the ankle-foot rehabilitation robot designed in this article is cost-effective.

INDEX TERMS
Characteristics of muscle movement, strategies of static and dynamic rehabilitation, completely decoupled, optimal design of dimensions, dynamic simulation.

I. INTRODUCTION
With the development of our society and the gradual maturity of the medical rehabilitation system, people are increasingly aware of the importance of medical rehabilitation for restoring normal physical conditions. Rehabilitation robots as modern medical aids are increasingly favored by injuries and medical staff. The ankle is a large load-bearing in the lower extremity of the human body. It has been under high load for a long time, and its special structure makes the ankle injury rate remain high in sports injuries. After the injury, the ankle function is unstable and the movement restriction is high. Hemiplegia caused by stroke also causes a sharp decline in the health of the ankle and its surrounding tissues. Therefore, the researches including the ankle rehabilitation exercise planning, and the rehabilitation mechanisms development are of great practical significance. It can well help all kinds of ankle patients recover their health.

Based on the needs of modern medical rehabilitation systems for medical rehabilitation equipment, in recent years, scholars in related area have successively carried out research work on ankle rehabilitation robots. Zhang et al. [1] designed a new type of uncoupled RR-RURU two-rotation ankle rehabilitation robot, and simulated it using clinical medical gait analysis data, the mechanism has good mechanical properties. Li et al. [2], [3] developed a parallel ankle rehabilitation robot, which has a force/torque information acquisition platform, which can realize passive, active and human-machine
interactive training of the ankle. Besides, the working space of the mechanism and the maneuverability and dexterity have been analyzed, which proves that the mechanism has good kinematic performance. Wang et al. [4] proposed a rigid-flexible hybrid-driven robot for ankle-assisted rehabilitation training. It can avoid secondary injury to the ankle and calculated the energy consumption of the machine. Liao et al. [5] proposed a hybrid rehabilitation robot. The hybrid rehabilitation robot can not only realize three kinds of ankle rehabilitation exercises, but also eliminate singularities and improve working space. Zeng et al. [6] used the screw theory to analyze the kinematics and related performance of a new parallel decoupling ankle rehabilitation mechanism, and using genetic algorithm to optimize and verify the rod size of the decoupling mechanism. Wang et al. [7] proposed a 3-SPS/S parallel ankle rehabilitation robot that can perform passive rehabilitation training mode, active rehabilitation training mode and intelligent voice rehabilitation training mode with 3 degrees of freedom. However, the rotation center of the robot is located on the sole of the foot and does not coincide with the actual rotation center of the ankle, which poses a certain risk of secondary injury. The mechanisms involved in the above research have good spatial and kinematic performance, but no specific ankle rehabilitation exercise strategy is proposed, which is mainly biased towards the theoretical design of rehabilitation mechanisms.

Considering the actual human-computer interaction during the rehabilitation process, the Rutgers ankle robot proposed by Girone et al. [8] is a hydraulic driven six degrees of freedom parallel device, which allows the treatment personnel to carry out rehabilitation training under virtual simulation conditions, and has achieved good treatment effect for ankle stroke and muscle injury around the ankle, but the residual degree of freedom of the mechanism increases the control complexity. Jamwal et al. [9] proposed a lightweight and compliant parallel ankle rehabilitation robot by placing a pneumatic muscle actuator parallel to the patient’s tibia, and developed an interactive training paradigm based on impedance control. Chen et al. [10] designed and manufactured electric ankle-foot orthosis using shape memory textile composite materials. The above researches will better integrate the physiological structure of ankle with rehabilitation machine and its movement, and the rehabilitation process will be more humanized, but this requires a well-performance controller. Since medical rehabilitation equipment is faced with a complex human structure. Yao [11] analyzed the rotation axis of the ankle based on the principle of nutrition, and used the AnyBody software to simulate the muscle activity in the rehabilitation exercise of the ankle. Then, a rehabilitation trajectory plan within a safe range is proposed. Gu [12] designed a walking assist device based on the study of the peak of muscle force, and proved that the device can provide auxiliary force for walking. Prokopios [13] and others studied the influence of ankle exoskeleton strength and movement timing on gait changes, and proved that applying a certain assist force at 48% of gait time can reduce the Lyapunov index at the ankle. The research and development of gait mutation exoskeleton machine provides reference for something. In summary, the research and development of rehabilitation robots based on physiological characteristics are more targeted and effective.

As the basis of human body movement, skeletal muscle’s health will directly affect the state of movement. Training of strengthening muscle strength can improve the stability of the ankle [14]. Yu et al. [15] found that the injury mechanism of ankle instability has different theories, but they are all related to weakening of muscle strength. At present, muscle strength training around the ankle and muscle strength training around the hip and knee are mainly used to strengthen the stability of the ankle. For restricted ankle motion and loss of active ankle motion due to hemiplegia, strengthening the exercise training of the surrounding muscle groups can improve muscle activity and provide protection for the health of the ankle. Lu et al. [16] used an ankle rehabilitation robot system for auxiliary intervention treatment, which can effectively improve the compliance of the soft tissue of the ankle in spastic hemiplegia in a short time, reduce the contracture of the plantar flexor muscle, and improve joint movement disorders. Therefore, a rehabilitation exercise program combining the characteristics of muscle movement with ankle-foot movement can provide novel strategies for ankle rehabilitation.

In order to achieve more comprehensive ankle-foot rehabilitation training, this paper firstly carries out human motion simulation experiments through human musculoskeletal model, analyzes the relationship between ankle-foot peripheral muscles and ankle-foot movement, and formulates ankle-foot rehabilitation movement strategy related to muscle assisted rehabilitation training; Secondly, to meet the needs of ankle rehabilitation training and realize the independence of mechanism control, a four degrees of freedom completely decoupled ankle-foot rehabilitation robot based on 2-CPFR-PU/R series-parallel hybrid mechanism is proposed, and its forward kinematics solution is obtained. Thirdly, according to the physiological characteristics of ankle and foot, the structure and size of the robot are optimized to achieve the optimal workspace and mechanical performance. Finally, the dynamic simulation experiment of the rehabilitation robot is carried out, and the results show that the robot has good dynamic performance.

II. ANALYSIS OF THE INFLUENCE OF MUSCLE AND ANKLE-FOOT MOVEMENT

As an important part of the human body, skeletal muscles have a great role in maintaining the body’s movements. The generation of strength is often accompanied by the contraction of skeletal muscles. A centripetal contraction is a form of contraction in which skeletal muscles actively exert force and also realizes the basis of various sports. Therefore, measuring the state of muscles during ankle movement and its impact on exercise will provide a theoretical basis for the development of corresponding rehabilitation strategies.
A. RESEARCH ON THE EFFECT OF MUSCLE ON ANKLE AND FOOT MOVEMENT POSITION

In order to solve the problem of human motion simulation, Frank [17] of Stanford University has developed OpenSim, which is an open-source software for human musculoskeletal model development, simulation and motion analysis. The main source of OpenSim’s human modelling theory for the Hill equation and Hill three-element model. The developers had ensured that the software has been thoroughly tested, the models and simulations accurately represent the essential physical phenomena [18]. Through the simulation study of OpenSim, the neuromuscular mechanism of abnormal gait such as hemiplegia gait and parkinson’s gait can be explored, which provides a basis for the improvement and improvement of abnormal gait rehabilitation methods [19]. Edith M et al. [20] studied how muscle fiber lengths and velocities affect muscle force generation as humans walk and run at different speeds through OpenSim, the study presents data that permit lower limb muscles to be studied in unprecedented detail by relating muscle fiber dynamics and force generation to the mechanical demands of walking and running.

DeMers and colleagues [21] used OpenSim to compare the effectiveness of reflex control and preparatory co-activation in preventing ankle injuries. Their simulations used a full-body musculoskeletal model with muscle stretch reflexes and preset muscle activation controllers. The model also included an elastic foundation contact model to compute foot–floor contact forces, and passive force elements that modeled the mechanics of ankle ligaments. The musculoskeletal and neuromuscular controller models, software, and simulation results from this study are freely available.

In order to test the effect of muscles on the ankle angle during falling and after landing, this paper uses the musculoskeletal model used by DeMers to conduct further experiments and research. The model consists of the trunk, pelvis and two legs, with a total of 23 degrees of freedom and 70 tendons. There are 12 tendons around the ankle-foot of one leg. The controller is a simplified version of the stretch reflex generated by muscle spindles that detect lengthening of muscle fibers. The reflex controller responds to whole muscle–tendon lengthening speed and is not isolated to lengthening speed of the muscle fiber. Additionally, there is no transmission delay between stretch detection and eliciting a muscle excitation, and the model does not include all the passive structures that resist motion of the ankle. The experimental model was made to fall freely from a single leg at a height of 0.2m to the ground, and the changes of ankle angle and subtalar joint angle in the whole process were simulated and tested. The ankle angle is mainly the dorsiflexion/plantarflexion azimuth angle (dorsiflexion is +, plantarflexion is −), the subtalar joint angle is the compound azimuth rotation angle of the foot eversion and internal and external rotation (inversion/external rotation is +, eversion/external rotation is −), and the exercise duration is set to 0.3s. The front and side view of the human experimental model under the initial posture is shown in Fig.1.

Set the normal state of the muscle as the control group and design the experimental group. In each experimental group, a certain muscle is disabled. The name of the disabled muscle and the corresponding experimental number are shown in Table 1.

According to the experimental results, the muscles corresponding to experimental groups 1, 2, 9, 10, and 11 had basically no effect on the dorsiflexion/plantarflexion and eversion/inversion during drop landing. Experiments 5, 6 show that the peroneus brevis and peroneus longus muscles have little effect on the rotation angle of the ankle, but have a greater influence on the rotation angle of the subtalar during falling, as shown in Fig.2, indicating that the peroneus brevis...
FIGURE 3. The angle of the ankle and subtalar changes when a certain muscle of the experimental model fails, compared with the Reference group. A represents the ankle rotation angle, S represents the subtalar rotation angle. (a) Lateral/Medial gastrocnemius muscle failure. (b) Soleus muscle failure. (c) Posterior tibial muscle failure. (d) Anterior tibial muscle failure.

and peroneus longus muscles act on foot inversion/eversion, and their pathology will have a serious impact on people’s foot inversion and eversion during normal walking.

The results of experiments 3, 4 are shown in Fig.3(a), the results of experiment 7 are shown in Fig.3(b). It can be seen that the medial gastrocnemius and soleus muscle have a greater influence on the ankle rotation angle. The failure of the medial gastrocnemius muscle reduces the peak ankle dorsiflexion angle after landing by 35.5%, and the peak ankle dorsiflexion angle increases by 63.3% after the soleus muscle fails. Indicating that the gastrocnemius and soleus muscles play a significant role in maintaining the normal posture of the human body after the human body touches the ground.

It can be seen from experiments 8 and 12 that the failure of the posterior and anterior tibial muscles will respectively reduce and increase the ankle dorsiflexion angle during landing. In addition, when the posterior tibial and anterior tibial muscles fail, the angle of the subtalar joint is close to 1.5 degrees during the free fall of the human body. In Fig.3 (c) and Fig.3(d), it shows that the failure of the posterior tibial and anterior tibial muscles has a greater effect on the ankle inversion and internal rotation movements, and it can be speculated that these two normally act on the ankle inversion and internal rotation movements.

B. RESEARCH ON THE RELATIONSHIP BETWEEN MUSCLE ANDANKLE-FOOT EXERCISE INTENSITY

Muscle metabolism value is proportional to the calorie consumption during the process of shortening/elongation. Muscle movement is mainly divided into centripetal contraction, eccentric contraction and isometric contraction. Centripetal contraction is the main form of muscle movement and the basis for achieving dynamic exercise, the muscle length is shortened, which is expressed as active movement. Eccentric contraction can achieve cushioning, braking, deceleration and overcome gravity, the muscle length is elongated, which is expressed as passive resistance exercise. Isometric contraction plays a role in supporting, fixing, and maintaining a certain body posture, the muscle length remains unchanged. During the dynamic walking exercise, it mainly shows the centripetal contraction and eccentric contraction of the muscle, so the strength of muscle contraction can be judged by the change of the muscle metabolism value.

In order to test the changes of muscles during the dynamic movement of the human body, the gait10dof18musc model in OpenSim is used as the experimental model [22]. Firstly, the normal calculation of gait is simulated by the muscle calculation control tool CMC (Computed Muscle Control). The movement law of the ankle in normal gait is shown in Fig.4.

The metabolic value calculator in the model calculates the metabolic rate of each muscle and the energy consumption of all muscles in the gait cycle [23], including the metabolic values of the gastrocnemius muscle, soleus muscle, and anterior tibial muscle. The results are shown in Fig.5.

As can be seen from Fig.5, the peak of gastrocnemius muscle and soleus muscle metabolism occurs in the process of ankle dorsiflexion to ultimate planterflexion. The soleus muscle metabolism is mainly in the ankle dorsiflexion stage. The metabolism of the gastrocnemius muscle mainly occurs
during the decrease of the angle of the ankle. In a small process, the metabolism of the tibialis anterior muscle is almost at the stage of ankle angle increase. The results correspond to the previous landing experiments, indicating that the gastrocnemius muscle mainly acts on the ankle plantarflexion and the anterior tibia muscle mainly acts on the ankle dorsiflexion.

C. ANKLE-FOOT REHABILITATION TRAINING PLAN COMBINING MUSCLE CHARACTERISTICS

According to the results and analysis of the above two experiments, the surrounding muscles of the ankle-foot are closely related to the movement of the ankle-foot. Functional training of the corresponding muscles is indispensable in the rehabilitation of ankle and foot injuries. From this, formulate rehabilitation exercise strategies related to muscle assisted training. After a series of on-site investigations in the rehabilitation department of local hospitals, a static rehabilitation exercise strategy and applicable injury conditions were obtained, as shown in Table 2.

In the static rehabilitation mode, the doctor recommends that the patient firstly moves slowly from the initial position to the training position for 5 seconds, stays in the endurable position for 10 seconds, and slowly returns to the original position for 5 seconds, 20 times a day. On the basis of the static rehabilitation strategy, when combined with the front and rear linear traction movement in the range of 10-200mm, it will be used as a dynamic rehabilitation exercise strategy. And the law of ankle movement under normal gait (as shown in Fig. 4) is used as one of the dynamic rehabilitation training plans.

### III. DESIGN OF ANKLE-FOOT REHABILITATION MECHANISM

In order to realize the static/dynamic rehabilitation exercise strategy formulated, this paper proposes a 2-CPRR-PU/R serial-parallel hybrid mechanism, where P, U, C, and R respectively represent the sliding pair, Hooke’s joint, cylindrical pair, and turning pair. As shown in Fig. 1, the 2-CPRR-PU parallel mechanism consists of a static platform, a dynamic platform, a PU branch chain (branch chain 1) and two identical CPRR branch chains (branch chain 2, branch chain 3). The series R pair is connected to the mechanism moving platform.

Let point $B_i$ and $A_i$ ($i = 1, 2, 3$) be the center of the motion pair connected to the moving platform and the fixed platform in branch $i$ respectively. Establish a fixed coordinate system $O − XYZ$ at the center of the static platform, the $Z$ axis is perpendicular to the static platform, and the $Y$ axis coincides with the center line $O_0A_0$ of the static platform. Establish a moving coordinate system $O_1xyz$ at the center of U pair of branch chain 1, the $z$ axis is perpendicular to the moving platform, and the $x$ axis coincides with the $O_1B_1$ axis. To describe the posture of each branch chain, a branch system $A_i(x_iy_iz_i)$ is established at the point $A_i$, the $z_i$
axis are perpendicular to the static platform, and the $y_i$ axis are parallel or coincident with the center line $OA_0$ of the static platform. The direction of each coordinate is shown in Fig. 6.

A. DEGREE OF FREEDOM ANALYSIS OF THE MECHANISM

According to the spiral theory, the motion spiral of branch chain 1 is

$$S_{11} = (0 \ 0 \ 1 ; \ 0 \ 0 \ 0)$$
$$S_{12} = (1 \ 0 \ 0 ; \ 0 \ 0 \ 0)$$
$$S_{13} = (0 \ 0 \ 0 ; \ 1 \ 0 \ 0)$$ (1)

From the motion spiral of (1), the constraint spiral system is

$$S'_1 = (0 \ 0 \ 1 ; \ 0 \ 0 \ 0)$$
$$S'_2 = (0 \ 0 \ 0 ; \ 1 \ 0 \ 0)$$
$$S'_3 = (1 \ 0 \ 0 ; \ 0 \ 0 \ 0)$$ (2)

In the above three constraint spirals, the movement of the moving platform in the $Z$-direction is restricted by $S'_{11}$ the rotation of the moving platform in the $Y$-direction is restricted by $S'_{12}$ and the movement of the moving platform in the $X$-direction is restricted by $S'_{13}$.

The motion spiral of branch chain 2 is

$$S_{21} = (0 \ 0 \ 0 ; \ 0 \ 1 \ 0)$$
$$S_{22} = (0 \ 0 \ 1 ; \ 0 \ 0 \ 0)$$
$$S_{23} = (0 \ 0 \ 0 ; \ a_3 \ b_3 \ 0)$$
$$S_{24} = (0 \ 0 \ 1 ; \ a_4 \ b_4 \ 0)$$
$$S_{25} = (1 \ 0 \ 0 ; \ 0 \ b_5 \ c_5)$$ (3)

$a_i, b_i, c_i$ is the real number of the corresponding position of the $i(i = 1, 2, \ldots, 5)$th motion spiral in branch chain 2.

According to the motion spiral of (3), the constraint spiral system is

$$S'_{21} = (0 \ 0 \ 0 ; \ 0 \ 1 \ 0)$$ (4)

This constrained spiral represents a force couple, which limits the rotation of the moving platform about its $Y$ axis. The motion spiral of branch chain 3 and branch chain 2 is the same as the constraint spiral. The three branches impose three restraining couples in the same direction on the moving platform, which are linearly related and have two redundant constraints, namely $v = 2$.

Using the modified Kutzbach-Gübler equation [24] to calculate the degrees of freedom of the 2-C PRR-PU parallel mechanism,

$$M = 6(n - g - 1) + \sum_{i=1}^{g} f_i + v - \xi$$
$$= 6 \times (9 - 10 - 1) + 13 + 2 - 0 = 3$$ (5)

In the formula, $M$ is the degree of freedom of the mechanism; $n$ is the number of purchased parts including the frame; $g$ is the number of moving pairs; $f_i$ is the degree of freedom of the $i$-th moving pair; $v$ is the multi-ring parallel mechanism in removing common constraints The number of redundant constraints after; $\xi$ is the local degree of freedom existing in the mechanism.

It can be seen that the mechanism has three degrees of freedom, and it can also realize the rotation around the $X$ and $Z$ axis and the movement along the $Y$ axis. A rotating pair about the $Y$ axis is connected in series on the moving platform of the 2-C PRP-PU parallel mechanism, so the 2-C PRP-PU/R series parallel hybrid mechanism is a four-degree-of-freedom mechanism with three rotations and one movement.

B. FORWARD KINEMATICS SOLUTION OF THE MECHANISM

According to the selection principle of input kinematic pair of decoupled parallel mechanism [25], the P pair of branch chain 1 is taken as the first motion input pair of mechanism, its input is represented by $l_1$, and the corresponding output is the rotation angle $\alpha$ of the moving platform along $x$ axis. The rotation pair perpendicular to the static platform of the U pair of the branch chain 1 is taken as the second motion input pair of the mechanism, its input is represented by $l_2$, and the corresponding output is the rotation angle $\beta$ of the moving platform along the $y$ axis. The moving pair of the C pair of the branch chain 2 is taken as the third motion input pair of the mechanism, its input is represented by $l_3$, and the corresponding output is the rotation angle $\chi$ of the moving platform along the $z$ axis. The R pair in series in the moving platform is taken as the fourth motion input pair of the mechanism, and its input is represented by $\theta_4$, and the corresponding output is the $y$-direction displacement $\delta$ of the origin $O_1$ of the moving platform.

The initial state of the mechanism is shown in Fig. 7. From the figure, the relationship between the input and output of the mechanism is

$$\alpha = \arcsin\left(\frac{l_3}{|B_1B_2|}\right), \ \beta = \theta_4, \ \chi = \theta_2, \ \delta = l_1$$ (6)

$|B_1B_2|$ represents the $y$-direction distance between the center $B_2$ of the rotation pair connected to the branch chain 2.
According to (6), it can be concluded that there is a one-to-one correspondence between the output of each position of the mechanism and the input, which does not interfere with each other. It has the characteristics of complete decoupling in control, and there is no singular space in the mechanism, which can ensure the continuity of the motion space. The mechanism has good kinematics performance.

Let the 2-CPRR-PU/R serial-parallel hybrid mechanism be used as an ankle-foot rehabilitation robot. The x, y and z-direction rotation of the robot will correspond to the plantarflexion/dorsiflexion, inversion/eversion, and internal/external rotation of the ankle, respectively. The decoupling characteristics of the robot will make the robot easy to control when it implements the static rehabilitation movement specified in Table 2, and the Y-direction movement freedom of the robot will realize the forward and backward traction required for dynamic movement rehabilitation.

### IV. OPTIMIZATION OF ROBOT STRUCTURE AND SIZE

When the foot moves, the ankle, talus, and talus often move together, so these threes are collectively called the foot joints. Talus is in the position of bony articular disc in the foot, that is, when the upper cavity is moving, it is mainly manifested as plantarflexion and dorsiflexion of the foot. The axis of the line, the calcaneus, scaphoid, and other foot bones rotate against the talus, which are mainly manifested as the inversion and eversion movement of the foot [26], [27]. It can be seen that in terms of structural design, the rotation axis of the ankle rehabilitation machine corresponding to the eversion orientation should be slightly lower than the rotation axis of the dorsiflexion orientation.

Combined with the rehabilitation exercise strategy formulated in Table 2, in order to meet the rehabilitation needs of most people, a survey of the ankle mobility shows that the average statistics of ankle dorsiflexion/plantarflexion, inversion/eversion, and adduction/abduction are roughly within a range [28], as shown in Table 3.

In view of the needs of rehabilitation training and the humanized setting of the machine, several size optimization goals of the robot are proposed, as shown in Table 4. The prerequisite for the robot’s all-directional motion angle to meet the physiological activity needs of the ankle. Optimizing the movement distance of the robot in the y-direction can expand the range of dynamic rehabilitation training activities to meet more dynamic training requirements. Reducing the overall size of the robot is conducive to improving the space utilization rate. It also makes the structure more compact and improves the mechanical performance of the robot. Limiting the height from the ground at the center of the ankle can make the robot more humanized and improve human comfort. Optimizing the length of the cantilever beams in the branch chain 2 and 3 can improve the mechanical performance of the robot and improve the smoothness of the machine movement.

The labeling of the dimensions of each part of the robot is shown in Fig. 7. Since the branches 2 and 3 are the same and symmetrical about the center line $OA_0$ of the static platform, only the relevant components of the branch 2 can be optimized. Where $a$ and $b$ represent the width and length of the moving platform. $c$ represents the length of the pendulum rod of the series R pair on the moving platform, and $d$ represents the width of the pedal. $e$ is the distance of the $z_2$-axis of the branch coordinate system of the branch 2 relative to the fixed coordinate axis $Z$ in the X-direction. $h$ is the distance from the U side of the branch 1 to the static platform. $t_1$, $t_2$, $t_3$ are the lengths of the first, second, and third members of branch chain 2 in order. $t_4$ represents the $z$-direction distance between the point on the moving platform connected to the branch chain 2 and the origin $o_1$ of the moving platform coordinate system. $t_5$ represents the length of $|B_1B_2|$ in Fig. 6.
According to the size of the human ankle, we can set the values of \( b, c \) and \( d \).

\[
\begin{align*}
  b &= 310 \text{ mm} \\
  c &= 80 \text{ mm} \\
  d &= 140 \text{ mm}
\end{align*}
\]  

(7)

Considering that the ankle-foot subtalar axis is slightly lower than the ankle axis, and ankle-foot varus is mainly produced by the subtalar, in order to meet the space required for human foot varus, the position of the series R pair should be adjusted reasonably. The positional relationship of related components in the inversion and eversion direction is shown in Fig.8(a). To avoid interference in the extreme position, the value range of \( \alpha \) should be

\[
a \geq 2\sqrt{c^2 + d^2/4} \sin(\beta + \arctan(d/2c))
\]  

(8)

Optimize the relevant dimensions of the robot’s dorsiflexion movement direction of the foot, and the positional relationship of the corresponding robot related rods is shown in Fig.8(b). The involved dimensions are \( t_1, t_2, t_4, t_5, h, \alpha \), and \( j \). Where \( j \) is the length of \( t_2 \) in this azimuth, and is related to the values of \( \delta \) and \( \chi \), but does not affect the relationship between \( t_1 \) and \( h \). So we will not consider it for the time being, \( t_1 \) must meet the mechanism at the plantarflexion/dorsiflexion limit position of the mechanism, so

\[
\begin{align*}
  t_1 &= h + \sqrt{t_4^2 + t_5^2} \sin(\alpha - \arctan(t_4/t_5)) \\
  0 &\leq t_1 \leq 300 \text{ mm} \\
  h &\leq 250 \text{ mm}
\end{align*}
\]  

(9)

Due to the existence of the series part, in order that the series part will not interfere with \( h \) in the \( z \)-direction displacement, the length of \( t_4 \) is constrained, namely

\[
t_4 \geq \sqrt{c^2 + d^2/4} + \varepsilon
\]  

(10)

where \( \varepsilon \) is the margin left to avoid interference at the limit position, and \( \varepsilon = 12 \text{ mm} \) can be taken.

Optimize the relative dimensions of the robot’s internal and external rotation movement of the ankle. The associated parameters are \( a, b, \varepsilon, t_2, \chi, \delta \), and \( g \). Where \( g \) is the \( y \)-direction projection distance between the center of the \( z \)-direction R side of the robot side chain 2 and the \( x \)-direction R side center of the side chain 1 in this view, then

\[
g = t_3 + \sqrt{t_4^2 + t_5^2} \cos(\alpha - \arctan(t_4/t_5))
\]  

(11)

In order to optimize the mechanical properties of the machine and reduce the length of the cantilever in the robot side chain 2, size constraints are imposed on \( t_3 \)

\[
50 \leq t_3 \leq 100 \text{ mm}
\]  

(12)

Since the driving of the robot corresponding to the dorsal plantarflexion movement is linear displacement, the value of the robot \( t_5 \) will affect the magnitude of the driving force. The larger the \( t_5 \), the smaller the driving force required, and the lower the robot dynamics requirements. Therefore, the size of \( t_5 \) is optimized. According to the positional relationship of the human ankle in the foot length, the optimization goal of \( t_5 \) is determined as

\[
3b/8 \leq t_5 \leq 3b/4
\]  

(13)

In order to limit the overall width of the robot and ensure that the robot can move in the \( y \)-direction under the internal and external rotation limits, according to the geometric relationship shown in Fig.8(c), the following size constraint relationship can be obtained:

\[
\sqrt{\frac{a^2}{4} + \frac{9b^2}{14}} \cdot \sin(\chi + \arctan(\frac{2\delta}{3b})) \leq \varepsilon \leq 200 \text{ mm}
\]  

\[
\delta \geq 200 \text{ mm}
\]  

(14)

\[
t_2 = \sqrt{\frac{\delta^2}{4} + \left(\frac{a^2}{4} + g^2 \cdot \cos(\arctan(\frac{2\varepsilon}{\alpha + \chi}))\right) \cdot \sin(\chi + \arctan(\frac{2\delta}{3b}))}
\]  

(15)

All the above size constraints on the robot need to meet all values in the three azimuth range of ankle-foot physiological movement. Considering the symmetry of the rehabilitation mechanism, the achievable range of motion suitable for the robot is given as

\[
-40^\circ \leq \alpha \leq 30^\circ \\
-20^\circ \leq \beta \leq 20^\circ \\
-20^\circ \leq \chi \leq 20^\circ
\]  

(16)

There are three main purposes for the mechanism to optimize the size, one is to make the mechanism meet the required working space, the second is to optimize the overall size of the
mechanism, and the third is to improve the overall mechanical performance of the mechanism. Considering that under the premise of satisfying the first two goals, improving the overall mechanical properties and stability of the mechanism has become the final optimization goal, so this optimization takes the minimum value of the cantilever beam size $t_2$ in the branch chains 2 and 3 as the final optimization goal. Let (15) be the optimization objective function and take its minimum value. According to the relationship between the parameters in (7)-(16), the numerical traversal algorithm of Matlab is used to calculate, and the value of each parameter corresponding to the minimum value of $t_2$ is obtained. The specific values are shown in Table 5.

| Optimization parameters | Final value /mm | Optimization parameters | Final value /mm |
|-------------------------|-----------------|-------------------------|-----------------|
| $a$                     | 233.28          | $t_2$                   | 208.07          |
| $b$                     | 310             | $t_3$                   | 124.58          |
| $c$                     | 80              | $t_4$                   | 80              |
| $d$                     | 140             | $t_5$                   | 121.30          |
| $e$                     | 177.02          | $t_6$                   | 126.25          |
| $h$                     | 250             |                         |                 |

Based on the final optimized size in Table 5, the robot is engineered, and the relevant size is adjusted and calculated reasonably according to the space required by the project. The modern 3D printer in the laboratory is used to 3D print the non-standard parts. After assembly, the prototype shown in Fig.9 was made. After testing, the robot can reach the limit position of all positions and achieve 200mm $Y$-direction translation at the rotation limit position, and the robot moves smoothly, which proves that the size optimization of the robot has a good effect. Therefore, it can ensure that the robot can meet the requirements of the extreme angle of motion in all positions in Table 2, and can complete the forward and backward movement of a certain distance required for dynamic rehabilitation.

### V. Dynamic Simulation Experiment of Ankle-Foot Rehabilitation Robot

The rehabilitation robot designed in this article can realize ankle-foot rehabilitation training in two modes: static and dynamic mode. Static training mainly corresponds to ankle range of motion training and stretching and contraction training of various muscles around the ankle and foot. Since the size of the robot has been optimized, the robot can achieve the maximum range of ankle and foot movements, and the robot has the characteristics of complete decoupling. The robot can perform independent or actions according to the law of the established static rehabilitation mode, which can ensure static rehabilitation the realization of training. In order to verify the simplification of robot control by the decoupling of the robot, and to test the overall mechanical performance of the robot, this section will simulate and analyze the dynamics of the robot during dynamic rehabilitation training.

Firstly, the human body is in a sitting position when the robot is performing rehabilitation training. The initial posture of the lower limbs and the horizontal range of motion of the ankle and foot are shown in Fig.10. $l$ is the trainer’s calf length (excluding ankle height) and $y_0$ corresponds to the initial position of the ankle (this time the calf vertical to the ground), $y_{\text{max}}$ and $y_{\text{min}}$ correspond to the positive and negative limit positions of the ankle, respectively. As shown in Fig.10, the displacement $\delta$ in $y$-direction will affect the angle of the trainer in the dorsiflexion/plantarflexion direction of the ankle. Since the total $Y$-direction displacement $\delta_m$ of the robot designed in this paper is small, the horizontal distance change of the knee of the trainer is ignored. The relationship between the $y$-direction displacement $\delta$ and the actual ankle angle $\alpha'$ is obtained as follows.

$$\alpha' = \alpha - \arcsin \left( \frac{\delta}{l} \right)$$  \hspace{1cm} (17)

The ultimate goal of rehabilitation is to restore the normal range of motion and movement of the ankle. Therefore, this article takes the angle of the ankle in the normal gait in the OpenSim experiment as the target rehabilitation motion track. Export the ankle angle change curve in Fig. 4 into a data format, and intercept and splice the original data segment according to the initial position of the robot and its corresponding gait node to obtain the target motion curve shown in Fig. 11(a). According to the Asian the average leg length [29], taking the trainer’s calf length as $l = 400$ mm, when the robot does not rotate in the $x$-direction, the change curve of the human ankle dorsiflexion/plantarflexion angle caused by the $Y$-direction displacement is shown in Fig.11(b). Substituting into (17), the $x$-direction rotation motion law
of the robot is shown in Fig. 11(c), and finally the inverse kinematics solution is solved according to (6), and the $x$-direction rotation of the robot in a motion cycle. The actual displacement time curve corresponding to the input assistant $l_3$ is shown in Fig. 11(d).

Then, the 3D model of the rehabilitation robot is saved in .x_t format and imported into the dynamic simulation software Adams. Then the material setting and connection relationship are added, and the corresponding driving pair and driving function are set. The curve shown in Fig. 11(d) is used as $l_3$ driving curve to drive the $x$-direction rotation of the robot. At the same time, according to the corresponding relationship between ankle angle and forward and backward movement displacement under normal gait, the driving function of robot $Y$-direction movement input is set. To simulate the load of human lower limbs on the robot, a force of 200N is loaded at the end of the robot, and the robot itself is also affected by gravity. According to the above settings, the dynamic simulation experiment of the robot is carried out. After the simulation results are processed, the $x$-direction rotation angle curve of the robot and the force variation curve of the driving pair $l_3$ are obtained, as shown in Fig. 12. According to the observation, the $x$-direction rotation angle change curve of the robot is basically consistent with the theoretical motion curve shown in Fig. 11(c). After converting the two curves into data and processing the two groups of data, the error between them is $\delta = 1.68\%$. For the non-precision motion value, the error value is small, which proves that the robot can realize the dynamic rehabilitation training under the target trajectory. As shown in Fig. 12, the driving force variation curve of the robot input pair $l_3$ is relatively gentle except that the peak value is unstable. When the robot branch chain 2 and branch chain 3 are driven synchronously, the dynamic peak value of each branch chain corresponding to $l_3$ is $F = \frac{170}{2} = 85$N, and the dynamic performance of the robot in $X$ direction is very well.

Finally, to verify the complete decoupling characteristics of the rehabilitation robot in kinematics, the united motion simulation of the robot was carried out to test its overall
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VI. DISCUSSIONS

In recent years, as the size of the medical device market has increased year by year, people’s understanding of rehabilitation has become deeper and deeper. The global drug/device per capita consumption ratio is 1:1. The global medical device market in 2018 was USD 427.8 billion, the annual growth rate is 5.63%, and there is a continuing upward trend, indicating that medical equipment has a huge demand in the world. A comprehensive ankle-foot rehabilitation equipment is needed in many places such as hospitals. The production of rehabilitation equipment can not only reduce the work intensity of most rehabilitation trainers, but also achieve more comprehensive rehabilitation training, provide convenience for doctors and patients, and improve the quality of life of patients.

From the comparison in the table, it can be seen that the robot designed in this paper has full degrees of freedom, a high degree of coincidence of the rotation center and the physiological rotation center of the ankle, a wide range of activities, high cost performance, and greater market competitiveness. Compared with the existing research on ankle equipment, in addition to the above advantages, it also has the characteristics of complete decoupling, and is independent and simple in control. Therefore, the robot designed in this paper can be considered as superior.

TABLE 6. Parameters of existing ankle rehabilitation equipment in the market.

| Device name                  | Function                          | Move- ment direct- ions | Coincide with the ankle center (F/T) | Dynamic movement (F/T) |
|------------------------------|-----------------------------------|------------------------|-------------------------------------|------------------------|
| Ankle training device        | Foot deformity correction         | 1                      | F                                   | F                      |
| Ankle CPM                    | Passive training for those with restricted range of motion | 2                      | T                                   | T                      |
| Elderly barrier-free exercise bike | Strength training of lower limbs  | 1                      | F                                   | T                      |
| Seated kick trainer          | Leg muscle training               | 1                      | F                                   | T                      |
| Seated ankle training chair  | Active and passive training of ankle flexion and extension | 1                      | F                                   | T                      |
| Hemiplegia rehabilitation device | Increase mobility                | 1                      | F                                   | F                      |
| The rehabilitation robot designed in this article | Comprehensive ankle rehabilitation training | 4                      | T                                   | T                      |

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VII. CONCLUSION

(1) This article analyzes the influence of different muscles on the rotation directions of the ankle joint, and designs a human free landing experiment to test the changes in the ankle angle during and after an abnormal landing, and measure the relationship between the changes in the metabolic value of different muscles and the changes in the ankle angle during normal walking. Therefore, a static and dynamic ankle rehabilitation training strategy for muscle activity training is proposed, and the ankle movement law under normal gait is taken as one of the dynamic rehabilitation exercise goals.

(2) In order to realize the static and dynamic rehabilitation exercise strategy formulated, this paper proposes a new type of decoupling serial-parallel hybrid mechanism with three rotations and one movement as an ankle-foot rehabilitation robot model. After analyzing its degrees of freedom and kinematics positive solution, it is proved that it is completely decoupled in kinematics and there is no singular space. It solves the problem that the parallel mechanism is difficult to control due to coupling, and realizes the independence of motion control in all directions.

(3) The structure of the robot is optimized. The rotation axis of the ankle rehabilitation machine corresponding to the eversion position is slightly lower than the rotation axis of the dorsiflexion/plantarflexion position, so that the robot rotation axis coincides with the ankle and foot movement axis. The robot movement direction corresponds to the front and back of the ankle-foot. The direction of movement allows the robot to achieve dynamic rehabilitation movement.
(4) Under the premise of meeting the space required for the implementation of the rehabilitation strategy, in order to reduce the overall size of the mechanism and improve the mechanical performance of the robot. This paper takes the cantilever beam as the final optimization goal, and uses the numerical traversal method in Matlab to find the optimal size solution. After printing the non-standard parts using 3D printing technology, the whole machine is assembled. Through the experiment, the robot has sufficient space for movement and smooth movement. (5) A dynamic simulation experiment is carried out with the goal of dynamic rehabilitation movement strategy, and the simulated movement of walking in a sitting position is performed. The results are the same as expected. When performing movement simulation of all positions, the robot’s motion control in all directions is independent and performs good dynamic performance. Which can proves that this new type of ankle and foot rehabilitation mechanism can satisfy ankle and foot rehabilitation training based on the characteristics of muscle movement.

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