Statics Analysis of 3-PRS Ankle Rehabilitation Robot

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***Abstract*:** Aiming at the rehabilitation training of the injured ankle, two prototypes of the ankle rehabilitation robots are proposed and selected and analyzed. Based on the parallel mechanism, two kinds of the 3-PRS ankle rehabilitation robots are designed in the paper. The first structure is that the moving platform is located above and the second structure is that the moving platform is located below. Two kinds of the 3-PRS ankle rehabilitation robots are applied with load, the static simulation under the different moving platform poses is performed and the analysis is carried out according to the static simulation results. The experiment shows that the structure of the 3-PRS ankle rehabilitation robot moving platform located below has higher stability and more reasonable stress analysis.

Keywords: *3-PRS parallel mechanism, Ankle, Rehabilitation robot, Statics analysis, ANSYS*

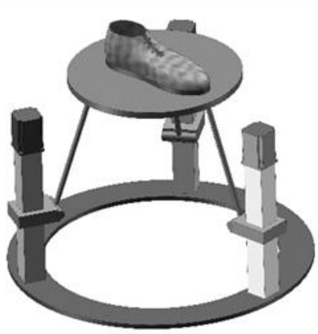
I. INTRODUCTION

The ankle is similar to a spherical joint in the mechanical connection, and it has two rotational degrees of freedom (DOF), which are plantar flexion/dorsiflexion and varus/eversion motion. In daily activities, most of the patients with ankle injury are injured in plantar flexion/dorsiflexion and varus/eversion. Some studies have determined the motion range of the ankle [1] and the maximum range is determined by the injury condition of each patient. Therefore, in the course of ankle rehabilitation training, the condition of ankle rehabilitation must be set according to each patient characteristics. At present, many ankle rehabilitation robots [2-5] had been developed in the market, which can make real-time adjustments according to the characteristics of patients. Most rehabilitation robots can only perform a single plantar flexion/dorsiflexion or varus/eversion, which cannot meet the needs of all patients. If the rehabilitation robot can perform plantar flexion/dorsiflexion and varus/eversion at the same time, and the efficiency of the rehabilitation training will be greatly improved. According to these requirements, the two new ankle rehabilitation robots with the 3-PRS parallel mechanism as the infrastructure are proposed, which have the characteristics of high adaptability and can meet many different types of rehabilitation movements. The two 3-PRS rehabilitation robots have two rotational DOFs and the two main rehabilitation movements plantar flexion/dorsiflexion and varus/eversion can be completed. In addition, the rehabilitation robot also has a movement DOF, which can adjust the moving platform according to the patient height, so that the rehabilitation training effect of the patient can reach the best.

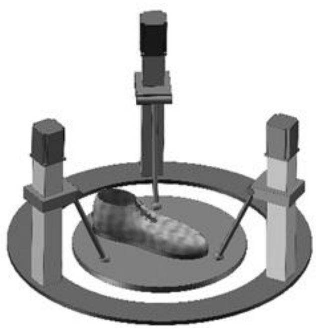
II. DESIGN OF 3-PRS ANKLE REHABILITATION ROBOT

According to the maximum range of movement [1], inertial parameters [6] and rotational moment [7-9] of the ankle in the process of motion, the design requirements of the 3-PRS ankle rehabilitation robot can be obtained. In the process of ankle movement, the angle of varus/eversion are greater than or equal to 20°, the angle of plantar flexion/dorsiflexion are greater than or equal to 20°, the moment of dorsiflexion is greater than or equal to 15Nm, the moment of plantar flexion is greater than or equal to 7Nm, the moment of varus is greater than or equal to 5Nm and the moment of eversion is greater than or equal to 4.5Nm. The rehabilitation robot is designed to simultaneously satisfy the two major movements of plantar flexion/dorsiflexion and varus/eversion.

According to the above design requirements, the prototypes of the two 3-PRS ankle rehabilitation robots are designed as shown in Figure 1.



(a) Plan A



(b) Plan B

Figure.1 3D model of two plans

In Figure 1, the column height is 400mm, the diameter of the base is 25mm, the diameter of the moving platform is 150mm, the length of the three connecting rods is 250mm respectively and the diameter of the connecting rod is 12mm of the 3-PRS ankle rehabilitation robot.

III. STRESS ANALYSIS OF 3-PRS ANKLE REHABILITATION ROBOT

The connecting rod not only needs to meet the strength condition but also needs to meet the stability condition of the compression bar. The safety factor method is often used to calculate the stability of the compression rod. The material of the connecting rod is set as structural steel. Considering the eccentricity of the load on the connecting rod and other reasons, the specified safety factor of the material stability is set as 3 and the yield strength is 235MPa.

The connecting rod of the rehabilitation robot is set as a cylindrical long rod with uniform texture, so the moment of inertia can be expressed as

$$I = \pi d^4 / 64 \tag{1}$$

where, the diameter of the connecting rod d is set as 12mm.

The critical force P_{cr} and critical stress σ_{cr} of the connecting rod can be expressed as

$$\begin{cases} P_{cr} = \dfrac{\pi^2 EI}{(\mu L)^2} \\ \sigma_{cr} = \dfrac{P_{cr}}{A} \end{cases} \tag{2}$$

where, the length of the connecting rod L is set as 250mm, the elastic modulus E is set as $200\ \text{GP}_\text{a}$, and the connections at both ends of the connecting rod are the spherical pair and the revolute respectively, so $\mu = 1$. According to Equation (2), σ_{cr} is equal to $284\ \text{MPa}$.

$$[\sigma] = \frac{\sigma_{cr}}{[n]_{\text{st}}} = 94.75\text{MPa} < \frac{235\text{MPa}}{1.5} = 156.67\text{MPa} \tag{3}$$

According to Equation (3), the stable allowable stress of the connecting rod is less than the strength allowable stress, so the maximum allowable stress of the two rehabilitation robot connecting rods is $94.75\ \text{MPa}$.

IV. SIMULATION OF 3-PRS ANKLE REHABILITATION ROBOT

As a mainstream software, ANSYS simulation software not only provides the most advanced technology for product design, but also provides some real structural mechanical properties for virtual prototype simulation with high degree of reduction. Following ANSYS 12.0, an intuitive and user-friendly Workbench is added. Common types of analysis in Workbench include the structural statics, the modal analysis, the contact problem analysis and the multi-physical field coupling analysis. The static analysis [10,11] is used to solve the stress and strain problem caused by external load when the mechanism is at rest. The basic process of analysis is shown in Figure 2.

In order to test whether the design of the two parallel mechanisms proposed in the paper meets the strength standards, ANSYS/Workbench is used to conduct the static mechanical analysis of the robot structure. The specific steps are as follows:

(1) Model import

The plans A and B of the 3-PRS ankle rehabilitation robot 3D model are established in SolidWorks. The established model is saved as x_t format and imported into ANSYS/Workbench software.

(2) Material definition

After the model is imported into the finite element analysis software, the material of each part is defined through the software internal material database or the input custom material parameters.

(3) Contact and constraint additions

In the 3-PRS ankle rehabilitation robot, there are many contacts between each part, so it is necessary to add correct contact and constraints. Because the gravity needs to be added in the model, a fix constraint needs to be added at the bottom of the base. The correct setting of constraints is the key to the whole model, which directly affects the validity and accuracy of the software calculation results.

(4) Meshing

The meshing is related to the accuracy and reliability of the whole simulation. Through preliminary observation and mechanical calculation, the maximum stress of the connecting rod can be obtained. Therefore, the quality of the three connecting rod meshing should be improved in order to obtain more reliable results.

(5) Loads applying

The 3-PRS ankle rehabilitation robot is subjected to gravity and forces applied by the affected limb. Since a person may be stand on the moving platform when the rehabilitation robot is statically placed, the weight of the human body and the instantaneous loads that occur during the mechanism movement are added to the static analysis. To sum up, the force (2000N) is applied to the sole, and the direction is vertical downward.

(6) Finite element software solution analysis

The stress, strain and total deformation of the whole robot are solved, the results are analyzed and the conclusions are drawn.

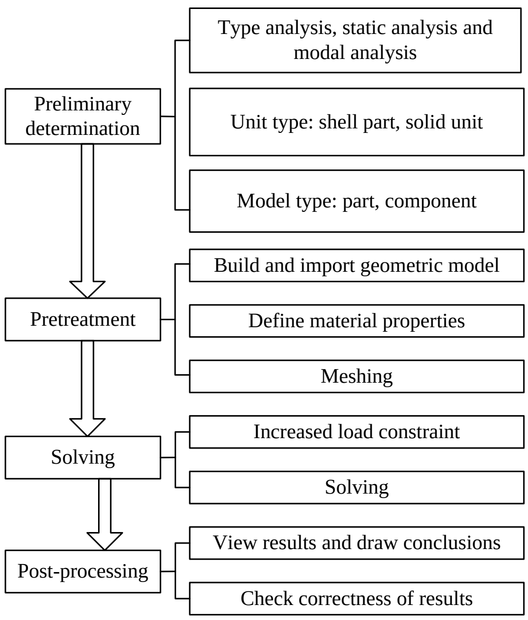


Figure. 2 Basic flow chart of static analysis

When the moving platform of the 3-PRS ankle rehabilitation robot stops at the different angles of plantar flexion/dorsiflexion and varus/eversion, the statics analysis of two plans A and B is carried out respectively. The maximum values of stress, strain and total deformation of typical angles in plan A and B during rehabilitation exercise are obtained, as shown in Table 1 to Table 4 respectively.

Table 1 Static analysis of plantarflexion in plans A and B

		0°	5°	15°	25°
Stress	A	43.020	57.381	62.993	96.770
（MPa）	B	37.918	31.709	32.446	31.227
Strain	A	2.1541	2.872	4.7576	4.8423
	B	1.8985	3.1407	1.6238	1.982
Deformation	A	0.69815	0.4321	0.72129	1.1713
（mm）	B	0.40068	0.29129	0.24739	0.25461

Table 2 Static analysis of dorsiflexion in plans A and B

		0°	5°	15°	25°
Stress	A	43.020	34.876	31.848	28.092
（MPa）	B	37.918	28.877	22.421	24.067
Strain	A	2.1541	1.7458	1.5926	1.4473
	B	1.8985	1.4457	1.1226	1.2052
Deformation	A	0.69815	0.57486	0.26779	0.2425
（mm）	B	0.40068	0.21792	0.12733	0.16558

Table 3 Static analysis of eversion in plans A and B

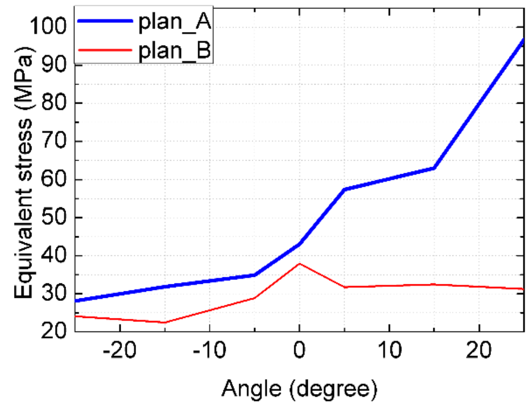
		0°	5°	15°	25°
Stress	A	43.020	43.131	54.007	64.354
（MPa）	B	37.918	29.230	40.670	54.107
Strain	A	2.1541	2.1703	3.0533	3.2221
	B	1.8985	2.7741	2.0339	4.8097
Deformation	A	0.69815	0.71755	0.74773	0.93411
（mm）	B	0.40068	0.27253	0.44344	0.44226

Table 4 Static analysis of inversion in plans A and B

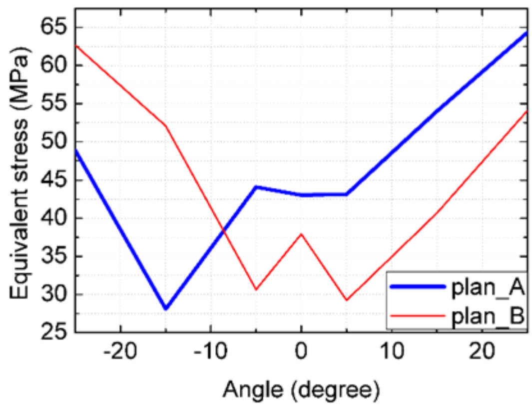
		0°	5°	15°	25°
Stress（MPa）	A	43.02	44.1	28.088	48.933
	B	37.918	30.646	52.065	62.706
Strain	A	2.1541	2.2078	1.4066	2.4498
	B	1.8985	1.5343	2.6067	3.664
Deformation	A	0.69815	0.71132	0.17542	0.63165
（mm）	B	0.40068	0.18212	0.52951	0.5078

From Table 1 to Table 4, it can be seen that the maximum stress value in plan A is generated when the plantar flexion motion reaches 25° and the maximum stress value is 96.77MPa. The maximum stress value in plan B is generated when the varus motion reaches 25° and the maximum stress value is 69.354MPa.

It can be seen from Table 1 to Table 4 that the strain values and total deformation values of the two plans are within a reasonable range, so the stress values are analyzed separately. The varus/eversion are the rotation of the platform around the *x* axis, but they are moving in different directions; in the same way, the plantar flexion/dorsiflexion are the platform rotating in different directions around the *y* axis. The stress data are summarized as two graphs of changes around the *x* and *y* axes, as shown in Figure 3.



(a) Plantar flexion/dorsiflexion



(b) Varus/eversion

Figure. 3 Maximum stress curves of plans A and B

The following conclusions are obtained from the analysis figure and table:

(1) In plan A, when the plantar flexion motion angle is 25°, the maximum stress reaches 96.77 MPa. In plan B, the maximum stress reached 64.354MPa when the varus motion angle is 25°. According to the analysis of Equation (2), Equation (4) can be expressed as

$$\begin{cases} 96.77\text{MPa} > [\sigma] = 94.75\ \text{MPa} \\ 64.354\text{MPa} < [\sigma] = 94.75\ \text{MPa} \end{cases} \tag{4}$$

According to Equation (4), Plan A is an unstable state, while plan B meets the intensity requirement.

(2) In Figure 3(a), both the magnitude of the maximum stress value and the change rate of the maximum stress value, plan B is far less than plan A. In Figure 3(b), the moving platform rotates around the *y* axis, so the structure has better support. The amplitude and rate of the maximum stress value change in plans A and B are within reasonable range. Therefore, it can be judged that the stress fluctuation range of plan B is small, it is not easy for the stress to increase or decrease rapidly, and the mechanism is more stable.

(3) Under the different angles of the different rehabilitation exercises, when the ultimate load of the mechanism is 2000N, the mechanism does not show large strain and total deformation, especially the strain value and total deformation value of the B plan are more stable.

To sum up, plan B is taken as the final design scheme of the 3-PRS ankle rehabilitation robot.

CONCIUSION

In order to improve the efficiency of rehabilitation movement, two kinds of the 3-PRS ankle rehabilitation robots are proposed and the model selection is analyzed by statics. Firstly, the two 3-PRS ankle rehabilitation robots are designed in the paper, one is the moving platform located at the above and the other is the moving platform located at the below. Secondly, the allowable stress of the two rehabilitation robots are analyzed and the maximum allowable stress of the connecting rod is obtained as $94.75\ \text{MPa}$. Finally, through static simulation analysis, the maximum stress, strain and total deformation under different attitudes are obtained. The experiment shows that the plan B of the 3-PRS ankle rehabilitation robot moving platform located below is more stable.

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