Advanced Materials Research Vol. 663 (2013) pp 515-521 *Online: 2013-02-13*
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doi:10.4028/www.scientific.net/AMR.663.515

Design of the Rehabilitative Apparatus for Ankle Joint Based on Parallel Mechanism and EMC2

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Keywords: Rehabilitative Apparatus; Ankle Joint; Parallel Mechanism; EMC2; Rehabilitative Training

Abstract. This paper adopts parallel mechanism to replace the traditional unarmed or simple mechanical device to offer better rehabilitative training on human body ankle joint, which can medically meet the demands of proceeding various training of motor rehabilitation on the ankle joint with an excellent application prospect. The design of the control system adopts t ier to operate and control. It can meet the various training requirements of users such as slow, continuous and reciprocating motion, and it can also design personalized training program based on the users' own condition. He open-EMC2 which makes it easy.

Introduction

The ankle joint is one of most paramount joints in the human lower limb which is mainly constituted by the bottom of tibia and fubula, trochlea of talus, as shown in the Fig.1. It can bear the weight of approximately five times the weight of a human body. In addition, its stability and flexibility play a paramount role in the lower limb locomotion [1]. The ankle joint's movement mode can be broken down into four categories: dorsiflexion movement (with the toe pointing upward); plantar flexion movement (with the toe pointing downward); varus movement (with the instep pointing inside); valgus movement (with the instep pointing outside). Generally, dorsiflexion and plantar flexion revolve around the intersection of planta and shank. Normally, their range of motion(ROM) is as follows: it is regarded as the position de repos when the planta and shank are approximately vertical. Then the normal ROM of the ankle joint's dorsiflexion and plantar flexion is separately within the range of 20 degrees to 30 degrees and 30 degrees to 50 degrees, and the total ROM of ankle joint is between 50 degrees to 80 degrees. While the ROM of varus and valgus is based on the angle between the instep and the ground plane which is within the range of 10 degrees to 25 degrees approximately. At the same time it should be noted that the activity velocity should be controlled between 0.5 degrees to 3.5 degrees per second when the patients are receiving rehabilitative training [2].

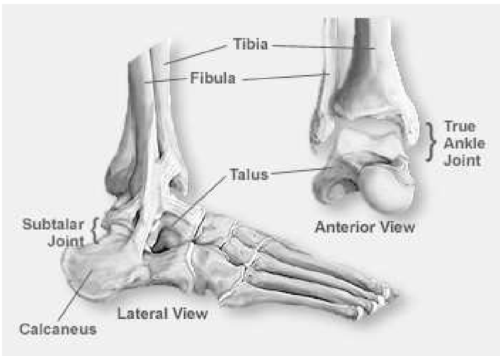

Fig.1 The structure chart of ankle joint

In the past a special medical staff helped the patient only by hands when the patient needed to the rehabilitative training on their ankle joint and that had the dorsiflexion, plantar, varus and valgus worked out in passive. However, it will be an extreme challenge for both patients and medical staff

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during the process of actual operation as the patient in the painful condition cannot use force on their own and the medical staff ought to be simultaneously cautious of the force's magnitude and orientation. In this case, no matter for the patient or the medical staff, they all urgently need a rehabilitative apparatus aimed at ankle joint to replace the medical staff to do the relative training of motor rehabilitation.

According to the survey, there have been several functionally similar rehabilitation apparatus [3]. All of them can be divided into two categories. The first category is manual, which requires the patient or the medical staff to control the ROM and time through simple lever mechanism only by hand. However, it has some deficiencies such as greater physical strength consumption of the users, lower accuracy and irregular rehabilitative training. The second category is automatic. Nevertheless, it can only do dorsiflexion and plantar flexion training for the ankle joint, meanwhile, its control system is too easy to meet users' demands of various training mode. In order to solve the shortcomings of the present rehabilitative apparatus and realize the overall rehabilitative training on the ankle joint, the design of this rehabilitative apparatus pays more attention to reinforcing the training flexibility [4]. Meanwhile, it adopts open-EMC2 control system which is aimed at meeting the various training requirements of users and designing personalized training program based on the users' own condition.

Design and Analysis

Functional Analysis. As shown in the Fig.2, the anticipated effect this rehabilitative apparatus can potentially achieve two aspects: a) the ankle joint movement and muscle stretch; b) dynamic balance training.

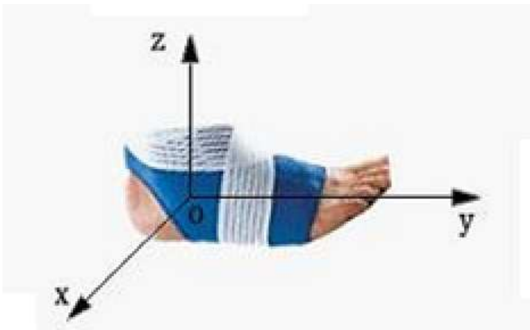

Fig.2 Spatial coordinate system based on ankle joint

Aimed at the ankle joint's dorsiflexion and plantar flexion movement, this rehabilitative apparatus will be able to revolve free around X-axis. Namely it needs X-DOF (degree of freedom) [6]. Similarly, this rehabilitative apparatus should be able to revolve free around Y-axis which is aimed at the ankle joint's varus and valgus movement. In other words, it needs Y-DOF.

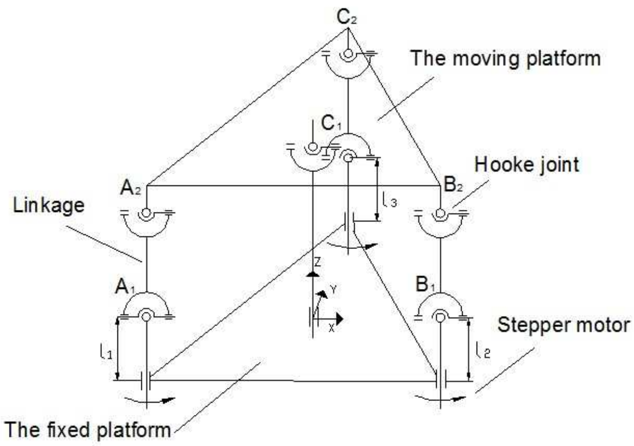

Fig.3 The mechanism of rehabilitation training apparatus

During the process of the ankle joint's movement, this rehabilitative apparatus also needs to stretch muscle in the key areas which can stimulate blood circulation, increase ROM of the ankle joint, improve compatibility of various muscle groups and soothe the tension of the muscle near ankle joint caused by pain. Simultaneously, this rehabilitative apparatus still needs to do dynamic balance training which can reinforce the compatibility of ankle joint and the muscle groups and improve the training effect of ankle joint further. In order to meet the demand of muscle stretch and dynamic balance training, a Z-DOF can be added to this rehabilitative apparatus (on the foundation of X-DOF and Y-DOF).

Overall, the rehabilitative apparatus needs a spatial parallel mechanism containing 3 DOF, which is X-DOF, Y-DOF and Z-DOF, in order to realize the rehabilitative training on ankle joint. The design of mechanism is shown in the Fig. 3[7].

Kinematics Analysis. Establish a stationary coordinate system $\Re$ on the fixed platform (the frame). And the coordinates of the drive shafts vertexes are $A_1(-a,-b,l_1)$, $B_1(a,-b,l_2)$, $C_1(0,b,l_3)$, respectively. Next establish a moving coordinate system $\Re'$ on the moving platform. Similarly, the coordinates of turning points on moving platform are $A_2(-a,-b,0)$, $B_2(a,-b,0)$, $C_2(0,b,0)$, respectively.

According to the Euler transformation matrix, the rotation matrix to transform the coordinates in the moving coordinate system $\Re'$ into the stationary coordinate system $\Re$ is:

$$\Re_0 = \begin{bmatrix} \cos\theta_y & \sin\theta_x \sin\theta_y & \cos\theta_x \sin\theta_y \\ 0 & \cos\theta_x & -\sin\theta_x \\ -\sin\theta_y & \sin\theta_x \cos\theta_y & \cos\theta_x \cos\theta_y \end{bmatrix} \tag{1}$$

Among them, θ_x, θ_y are the rotation angles that moving coordinate system $\Re'$ rotates around the stationary coordinate system $\Re$ on the X-axis and Y-axis. Then the coordinates of the turning points on the moving platform transformed into stationary coordinate system can be expressed as:

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \Re_0 \begin{bmatrix} x'_i \\ y'_i \\ z'_i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ h \end{bmatrix} \tag{2}$$

Namely the coordinates of three turning points, which is A_2, B_2, C_2, in the stationary coordinate system are $A_2(-a\cos\theta_y,-b\cos\theta_x,h-a\sin\theta_y+b\sin\theta_x)$, $B_2(a\cos\theta_y,-b\cos\theta_x,h+a\sin\theta_y+b\sin\theta_x)$, $C_2(0,b\cos\theta_x,h-b\sin\theta_x)$, respectively.

Supposing the length of linkage is C, then:

$$\begin{cases} (-a+a\cos\theta_y)^2+(-b+b\cos\theta_x)^2+(l_1-h+a\sin\theta_y-b\sin\theta_x)^2=c^2 \\ (a-a\cos\theta_y)^2+(-b+b\cos\theta_x)^2+(l_2-h-a\sin\theta_y-b\sin\theta_x)^2=c^2 \\ (b-b\cos\theta_x)^2+(l_3-h+b\sin\theta_x)^2=c^2 \end{cases} \tag{3}$$

In further derivation, we get the changing relationship between bar length and moving platform. That is, the inverse model is

$$\begin{cases} l_1=-\sqrt{c^2-(-a+a\cos\theta_y)^2-(-b+b\cos\theta_x)^2}+h-a\sin\theta_y+b\sin\theta_x \\ l_2=-\sqrt{c^2-(a-a\cos\theta_y)^2-(-b+b\cos\theta_x)^2}+h+a\sin\theta_y+b\sin\theta_x \\ l_3=-\sqrt{c^2-(b-b\cos\theta_x)^2}+h-b\sin\theta_x \end{cases} \tag{4}$$

According to the demand for training function of the rehabilitative apparatus, the moving platform should be able to rotate around X-axis from -50 degrees to 30 degrees, rotate around Y-axis from -25 degrees to 25 degrees and move within the range of 0 to 12 centimeters on the Z-axis. Given that the stationary and moving platform have turned θ_x around X-axis in the velocity of ω_x, turned θ_y around Y-axis in the velocity of ω_y, and moved z along Z-axis in the velocity of v_z, as shown in the following formulas:

$$\begin{cases} \theta_x = \omega_x t \\ \theta_y = \omega_y t \\ z = v_z t \end{cases} \tag{5}$$

With the aid of MATLAB, we can carry out the change curve of drive rod's length, as shown in the Fig.4.

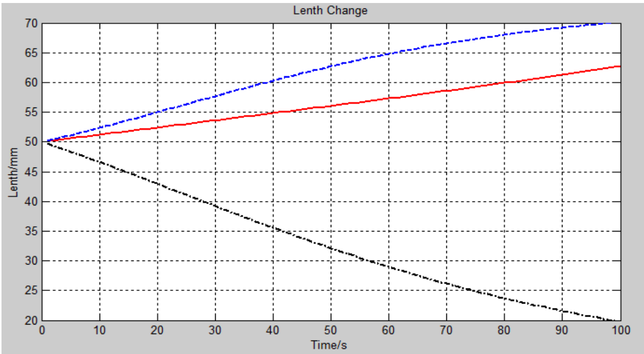

Fig.4 The changing curve of bar length based on MATLAB

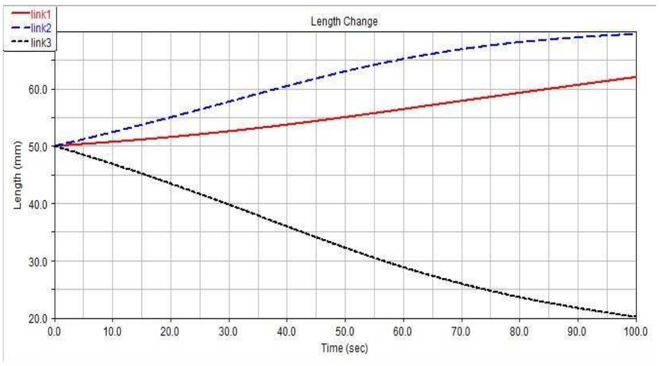

Fig.5 The changing curve of bar length based on ADAMS

In order to verify the accuracy of the model above, we established the model in ADAMS. When we load the functional expression (5) of rehabilitation movement onto the moving platform as driver[8], we are able obtain the change curves of drive rod's length as well, as shown in the Fig. 5. In comparison with the Fig. 4, their figures completely coincide which attests that the inverse model of this mechanism is right.

Design of Control System

The Correction of EMC2'S SC (source code) and Configuration Files. EMC2 is a controller developed by NIST (National Institute of Standards and Technology) which is to help PC replace special CNC control system. It possesses characteristics such as modularization, portability, scalability and open source [9].

In order to design the control system of this rehabilitative apparatus, we only have to rectify and compile the motion module in the EMC2' SC [10].

The motion module is compiled in C language and saved under the directory of src/ emc/ kinematics in the source package. We can observe many motion module which is built-in this system and calculations involvedis to find kinematics-Inverse-function which is in trivkins.c file and rectify it.

The ordinary functions of inverse kinematics based on rectangular coordinates are as follows:

```
joints[0] = pos->tran.x;
joints[1] = pos->tran.y;
joints[2] = pos->tran.z;
joints[3] = pos->a;
joints[4] = pos->b;
joints[5] = pos->c;
```

Among these functions, joints[] represents each joint's coordinate and the data in array pos locates the mechanism's position. In the above analysis, we have procured the relations of (l_1,l_2,l_3) and (θ_x,θ_y,z) , that is inverse model. What we all have to do here is to replace the relations of pos- > a, pos- > b and pos- > tran.z with joint[0], joint[1] and joint [2]. We have obtained the inverse function of joint[0], for example, which is organized and compiled in C language. Its code is as follows:

```
double pos0[30];
pos0[0]=l1;
pos0[1]=pos0[0]*pos0[0];
pos0[2]=-aa+aa*cos(B);
pos0[3]=pos0[2]*pos0[2];
pos0[4]=-bb+bb*cos(A);
pos0[5]=pos0[4]*pos0[4];
pos0[6]=-sqrt(pos0[1]-pos0[3]-pos0[5]);
pos0[7]=Z-aa*sin(B);
pos0[8]=bb*sin(A);
pos0[9]=pos0[6]+pos0[7]+pos0[8];
```

Upon completion of correction on inverse model, we should invoke the terminal which is in the kinematics' folder to compile by performing the order of sudo comp—install trivkins.c in order to complete the correction of EMC2'S SC. Then continue operating procedure, and the system will automatically generate configuration files for mechanism model. These files mainly contain INI file, HAL file, VAR file, TBL file, etc. Among them, we should do some relevant modification on the mechanism attributes which is INI file and then load it with the module of real-time motion, which is trivkins.c.

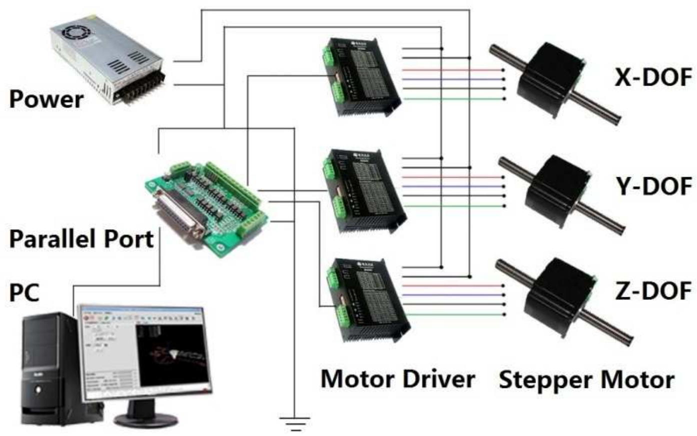

Fig.6 The hardware connection of auxiliary rehabilitative apparatus for ankle joint

Debugging and Compiling G Code. The control system of rehabilitative apparatus is shown in Fig. 6. In this system, EMC2 generates controlling signal by reading G code and transmits it to motor driver. Then according to the controlling signal, the motor driver drives step-motor. In this way, we can realize that to control the rehabilitative apparatus' movement on the 3 DOF directions, which is X-axis, Y-axis, Z-axis, by G code [11].

Analyzing inverse module and returning the initial state to zero, we will recognize the value of X-coordinate is the angle of the mechanism rotates around X-axis, the value of Y-coordinate is the angle of which the mechanism rotates around Y-axis and the value of Z-coordinate is the height of which the mechanism rises up or descends along Z-axis. Then modify and assemble the G code of which the ankle joint proceeds all sorts of training, therefore not only we can make all possible of training schemes in order to meet the users' multiple training demands such as slow, continuous and reciprocating motion, but it also can design personalized training program based on the users' own condition. The device in Fig. 7 is the auxiliary rehabilitative apparatus, which is contrived by our team, based on open-EMC2 control system.

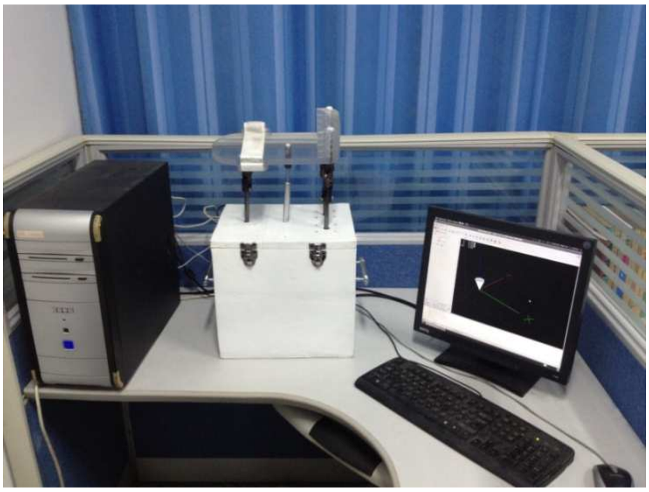

Fig.7 The rehabilitative apparatus for ankle joint

Conclusion

Through analyzing the motion feature of ankle joint, our team contrived the spatial parallel mechanism characterized by possessing three DOF, which is X-axis, Y-axis and Z-axis, as mechanism part of the rehabilitative apparatus. And through theoretical derivation and simulation verification, we procured the inverse model of this parallel mechanism. As a result based on the inverse model, we completed the control system design of on ankle joint which is based on EMC2, and realized the control of the auxiliary rehabilitative apparatus (on ankle joint). Not only can this rehabilitative apparatus do rehabilitative training on ankle joint systematically, but also it possesses the several characteristics such as simplicity of operation and ease to control. With all factors considered, it allows us to meet the users' multiple training demand with broad application prospect.

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10.4028/www.scientific.net/AMR.663

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