Dynamics analysis and simulation of a new 6-DOF lower limb rehabilitation robot

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Abstract. This paper proposes a new hybrid (parallel–serial) 6-DOF lower limb rehabilitation robot including two mechanical legs and an adjustable seat, which could train in sitting, lying and standing three postures. Each mechanical leg consists of hip joint, knee joint and ankle joint. The dynamics and DOF of the robot are analysed, and the result is verified by the software ADAMS. The result lay the foundation for prototype build in future.

1. Introduction
As many countries enter the aging society, how to ensure the living life of the elderly has become a focus problem [1, 2]. Stroke, a common disease in the elderly, has a high morbidity and disability to lower limb, spinal injury and physical weakness would also cause limb problems [3]. Rehabilitation training is widely regarded as an effective method to the mentioned diseases, which is based on neural plasticity [4, 6]. Rehabilitation robot, as an intelligent human-computer interaction robot system, could alternate traditional manual treatment, and it has developed rapidly in recent years.

LOKOMAT is the widely known lower limb rehabilitation robot, which is mostly used for walking training in later recover stage. LOKOMAT is equipped with weight support device and match treadmill, and it could realize the walking training and gait training [7]. A Switzerland company named SWORTEC developed a rehabilitation robot, MotionMaker, which consisted of two mechanical legs, and it has passive training, active training and functional electrical stimulation training [8]. An exoskeleton rehabilitation robot called iLeg was proposed by Zhang Feng, et al. It has two exoskeleton leg components and could achieve passive training and active training [9].

However, most of lower limb rehabilitation robots now are only applied to sagittal plane rehabilitation. It is necessary to develop a full-joint multi-pose lower limb rehabilitation robot. In this paper, a sitting, lying and standing multi-pose 6-DOF (degree of freedom) lower limb rehabilitation robot is presented.

2. Mechanical structure of rehabilitation robot
The 6-DOF lower limb rehabilitation robot consist of two symmetrical mechanical legs and an adjustable seat as shown in Fig. 1. Each mechanical leg is a 6-DOF hybrid (parallel–serial) mechanism which is composed of hip joint (2-DOF), knee joint (1-DOF) and ankle joint (3-DOF). Adjustable seat
could switch between sitting, lying and standing three modes to cooperate with mechanical legs to train in different posture.

![Lower limb rehabilitation robot.](image1)

2.1. **Hip joint**
The hip joint is multiaxial joint, which can realize extension/flexion and abduction/adduction two kinds of movements, as shown in Fig. 2. The hip joint has two DOF, and two rotating pairs are connected in series. If one of the rotating pairs is translated, the two connected rotating pairs can be regarded as a universal joint. Because the overload protection and vibration reduction of belt drive, the extension/flexion of the hip joint (the head of the transmission chain) uses the synchronous belt to achieve the motion.

![Hip joint and knee joint.](image2)

2.2. **Knee joint**
The knee joint has only one DOF as shown in Fig. 2. The transmission device is assembled in the mechanical crus, which could transmit power to the reducer and mechanical thigh and then realize the rotation between the crus and thigh.

2.3. **Ankle joint**
The ankle joint of rehabilitation robot can rotate in three different directions as shown in Fig. 3, which could provide comprehensive rehabilitation training for the ankle joint of patients. Inversion/eversion motion is controlled by motor through two crank, and pronation/supination motion is driven by electromotive handspike 1. The whole ankle joint will rotate around crus to realize dorsiflexion/plantar flexion motion, which is controlled by the motor in crus.

To adapt different hip width of patients, the distance between the two pedals of the rehabilitation mechanical can be adjusted by controlling the slider inside the ankle mechanism through
electromotive handspike 2. To accurately positioning the center of ankle rotation, the height of the pedal could be adjusted through the rotation of the knob.

3. Dynamics analysis of lower limb rehabilitation robot

As the lower limb movement of the human body mainly depends on the movement of thigh and crus, and the movement of ankle can be regarded as auxiliary movement, the general equation of dynamics could be obtained by Lagrange equation method.

Before the derivation of the dynamics formula, the centroid position of the ankle joint should be determined. Fig. 4 is a simplified linkage model of the ankle parallel joint. $A$, $B$, $C$, $D$, $E$, $F$, $G$ represent the rotating joint of the connecting rod; $O$ represents the pedal center of mass position; $\alpha_i$ represents the joint rotation angle of the link $BD$, the link $DE$ and the link $FG$ respectively; $c_i$ represents the position of the center of mass of each rod in the base coordinate system; $r_i$ represents the centroid position of the rods relative to the previous joint; $m_i$ represents mass of each link; $i_i$ represents the inertia of each the links to the base coordinate system.

Combined with the forward/inverse kinematics, the positions of the points $c_1$, $c_2$, $c_3$, $c_4$, and $c_5$ can be obtained by using the software MATLAB, and partial result is shown as follow:
The centroid of thigh, crus and ankle fixed platform could be calculated in the same method. The angular velocity and velocity of each link centroid could be obtained by:

\[
\omega_{i+1} = i^1 R \omega_i + \dot{\theta}_{i+1} z_{i+1}
\]  

\[
\begin{bmatrix}
X_{c_i}'

Y_{c_i}

Z_{c_i}
\end{bmatrix}
= m_i \begin{bmatrix}
c_2 (r_1 + r_3 s_5 - r_4 c_5 s_6) + (c_3 s_2 s_3 + c_3 c_2 s_4) (r_4 c_5 + r_4 s_5 s_6)

c_1 s_2 (r_1 + r_3 s_5 - r_4 c_5 s_6) - (r_3 c_5 + r_4 s_5 s_6) (c_3 c_5 s_2 + c_2 c_5 s_4) - s_4 (s_2 s_5 - c_1 c_2 c_3)

(r_4 c_3 + r_4 s_5 s_6) (c_4 (c_3 c_3 - c_2 s_3) s_4 - s_4 (c_2 s_5 + c_2 c_3)) + s_4 (s_2 s_5 - c_1 c_2 c_3)

-a_2 c_3 s_2 - a_2 s_5 + r_4 c_5 (s_2 s_5 s_6 - c_1 c_2 c_3)

-a_2 (s_2 s_5 - c_1 c_2 c_3) + a_2 c_3 s_2 - r_4 c_5 (c_2 s_5 + c_2 c_3) + s_4 (c_2 s_5 + c_2 c_3) + s_4 (c_2 s_5 + c_2 c_3)

-a_2 (c_3 s_2 + c_3 c_5) + a_2 c_3 s_2 + r_4 c_5 (c_2 s_5 + c_2 c_3) + s_4 (c_2 s_5 + c_2 c_3) + s_4 (c_2 s_5 + c_2 c_3)
\end{bmatrix}
\]  

\(1\)

Each link kinetic energy and potential energy of the mechanical leg mechanism could be obtained by equations as follow:

\[
E_{ki} = \frac{1}{2} M_i \left( v_{ki}^2 + v_{ki}^2 + v_{ki}^2 \right) + \frac{1}{2} I_i \omega_{ki}^2
\]  

\[
E_{pki} = M_i z_{ki}
\]  

\(4\)

The Lagrange function \( L \) is defined as the difference between the total kinetic energy and the total potential energy of the mechanical system, namely:

\[
L = K - P
\]  

\(6\)

The dynamics equation of the system (the second kind of Lagrange equations) is:

\[
\tau = \frac{d}{dt} \frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q}
\]  

\(7\)

Since there is no variable in the potential energy, the kinetic equation (7) becomes:

\[
\tau = \frac{d}{dt} \frac{\partial E_k}{\partial \dot{q}} - \frac{\partial E_k}{\partial q} + \frac{\partial E_p}{\partial q}
\]  

\(8\)

where, \( q \) represents joint variable; \( \dot{q} \) represents joint speed; \( \tau \) represents drive torque vector.

4. Dynamics simulation verification
Built virtual model in the software ADAMS platform, as shown in Fig. 5.
Add constraints to each component, and DOF simulation is shown in Fig. 6. The simulation result is 6-DOF robot, and the whole process has no redundant constraints.

**Figure 6.** Simulation verification result of DOF.

Import parameters (Table 1) of the motion track to model, and the simulation diagrams are shown:

### Table 1. Parameters of the motion track.

| Posture/Sagittal plane motion | Hip $\theta_1$ | Knee $\theta_2$ | Ankle $\theta_4$ |
|------------------------------|----------------|-----------------|-----------------|
| Sitting                      | $0^\circ$~$10^\circ$ | $-110^\circ$~$0^\circ$ | $-30^\circ$~$15^\circ$ |
| Lying                        | $0^\circ$~$30^\circ$ | $-30^\circ$~$10^\circ$ | $-10^\circ$~$10^\circ$ |

**Figure 7.** Dynamics data in sitting training mode.

**Figure 8.** Dynamics data in standing training mode.
Combined with ergonomics, the weight and inertia tensor of human body during rehabilitation training, the maximum torque of hip joint, knee joint and ankle joint is 150N/m, 50N/m and 6N/m respectively.

5. Conclusion
A new hybrid (parallel-serial) 6-DOF lower limb rehabilitation robot including two mechanical legs and an adjustable seat is proposed, which could train in sitting, lying and standing three postures. The dynamics and DOF of the robot are analyzed, and the result is verified by the software ADAMS. The result lay the foundation for prototype build.

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