Development of Skeletal Muscle Model for Bridge-Style Movement Rehabilitation

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Abstract. Currently, according to statistical data showed by world health organization, the aging problem has been becoming an extraordinary serious social challenge. China has become one of the countries with the largest elderly population and the fastest growth in the word. Compared with the traditional one-to one between therapist and patient, this paper proposed an intelligent bridge-style movement rehabilitation robot. The rehabilitation robot assisted patients to complete the bridge-style movement via auxiliary mechanism. Then, applying muscle parameters and skeletal muscle carried out the simulation analysis of the auxiliary mechanism. The results proved that the auxiliary mechanism performs well in the process of auxiliary bridge-style movement.

Keywords. Aging problem; bridge-style movement; muscle model.

1. Introduction
The stroke and hemiplegia are the common disease with high incidence and high disability rate among the elderly population [1]. Due to the shortage of medical resources, around eighty percent of stroke patient can’t get timely treatment, which can aggravate the patients’ condition and seriously affect their life [2]. In the current clinical treatment, most therapists adopt one to one therapeutic method that not only increases the work intensity of therapists, but also extends the rehabilitation cycle of patients. With the development of robot technology, the rehabilitation robot gradually applied to the clinical treatment. Its best characterized by ensuring the intensity, effect and accuracy of rehabilitation training and good consistency. The basic reason for hemiplegic patients lies in the damage of nervous system, which leads to unable to complete normal physiological activities. Bridge-style movement, as a necessary treatment in the early rehabilitation, is one of the most suitable movements for the hemiplegic patients [3]. Introducing bridge-style movement in the clinical practice can promote the patients’ nervous system remodeling, enhance body balance and strength control, improve the muscle control in the core areas and help the patients recovering basic walking function [4]. Thus, bridge-style movement is of great significance for the hemiplegic patients. However, in view of the different conditions of patients, a great number of patients can not complete the standard bridge-style movement, and even some patients can’t independently carry out the bridge-style movement, which prolong the rehabilitation cycle. Therefore, this paper proposed an intelligent bridge-style movement rehabilitation robot to help patients complete...
standard bridge-style movement.

In the past few years, many experts and scholars from home and abroad have carried out a series of researchers on rehabilitation robots. A lumbar rehabilitation robot has been developed by Chinese Academy of Sciences in 2012 [5]. Imamura et al. designed the elastic band passive assisting device by analyzing the corresponding output relationship between the waist bending posture and the back muscles, but its application was not high. The Federal Institute of technology in Lausanne has developed a Motionmaker waist robot. There are many rehabilitation robots aiming at lumbar training and later period training, but few for bridge-style movement training. Therefore, researching the intelligent bridge-style movement rehabilitation robot is of great significance. The rehabilitation robot is shown in figure 1.

The rehabilitation robot can track each state of the patients’ bridge-style movement via applying sensor tracking technology, and combine with skeleton-muscle judges whether the patients’ bridge-style movement conforms to the standard bridge-style movement. Finally, rehabilitation robot assists patients who can’t reach the standard bridge-style movement to complete rehabilitation training to achieve the standard bridge-style movement [6-8].

2. The Establishment of Bridge-Style Movement Skeletal Muscle Model

In the process of bridge-style movement, the hip joint is the main kinematical units. Meanwhile, the hip joint is one of the most important and complex joints. Establishing skeletal muscle model is the basis of studying bridge-style movement. This paper adopted engineering knowledge to solve medical problems. Through the combination of medical theory and engineering knowledge, the medical problems can be explored by engineering analysis. The analysis process of the skeletal muscle model is shown in figure 2.
2.1. Terminology of Human Body Structure
The hip joint is one of the most important and complex joints in the human joints. In the process of bridge-style movement, the hip joint is the main supporting and bearing part, which plays the connecting role. Adopting professional terms describe these coordinate planes and axes in rehabilitation medicine, including vertical axis, sagittal axis. Coronal axis, sagittal plane, coronal plane and horizontal plane as shown in figure 3a.

In order to simplify the motor direction, bridge-style movement aim at sagittal plane in clinical stage. Thus, it is necessary for patients to provide quantitative assessment. The standard posture of bridge-style movement, as shown in figure 3b, maintains as the shoulder, waist and thigh in the same line and thigh and crus meet at approximately right angles as possible.

2.2. The Skeletal Muscle System of Human Body
The bones participated in bridge-style movement are lumbar bone, hip bone, hip joint, femur, knee joint and patella as shown in figure 4a. Hip joint is the main joint of bridge-style movement, which can drive the rotation of the leg, including flexion/extension, inversion/eversion and internal/external as shown in figure 4b. The lumbar bone, femur and patella can be simplified as rigid rod. In order to simplify skeletal model, the DOF of the hip joints, knee joint and ankle joints is reduced to one, including flexion-extension as shown in figure 4c.

The bridge-style movement also has muscles attached to the bone. The muscles group around hip joint mainly include three parts, including hip muscles group, thigh muscle group and waist muscle group as shown in figure 4a. Waist muscles group mainly includes psoas major and psoas minor. The psoas major has the important function of maintaining the stability posture, transmitting the strength of upper and lower. The hip muscles are divided into two groups: anterior and posterior muscles. The anterior muscles mainly include iliopectineus, which main function is the external rotation and anteflexion
of hip joint. The posterior muscles mainly include glutes minimus, gluteus medius, gluteus maximus, which achieves the external rotation and extension of the hip joint and ensure the human balance and upright. Thigh muscle group mainly includes anterolateral, medial and posterior. The anterior thigh muscles mainly include tensor latissimus and sartorius. The key functional role of quadriceps femoris implements the stretching movement of hip joint.

2.3. Bridge-Style Movement Muscle Model
The human skeletal muscle model includes human motor characteristics, motor analysis and force analysis, which has important reference value. The muscle stretching force can be analyzed by establishing the bridge-style movement skeletal muscle model, which can be used as a guide for the rational design of auxiliary mechanism.

Through the analysis of muscle distribution and body bones, it is found that the skeleton should be hard enough, without considering the deformation of bones, and have the same geometric parameters as human body. Due to the complexity of human muscle, it is difficult to imitate the real human muscle in the process of bridge-style movement. Thus, adopting Hill model describes the change of muscle. It can reflect the characteristics of muscle contraction and elasticity, accurately describe the functional activities of muscle. And it can also reflect the relationship between muscle tension and speed and muscle tension and muscle length, which can make the qualitative or quantitative calculation of muscle force and analyze the force of hip joint in the bridge-style movement. The skeletal muscle model is shown in figure 5.

![Figure 5. Hill muscle model.](image)

X is the total length of tendons and muscles fiber, x1 is the length of tendons, x2 is the length of muscle fiber. This Hill muscle model is composed of contractile element, parallel elastic element represented by kparallel and series elastic element represented by kserial. The contractile element represents the activity performance of muscle fiber, which can reflect the elasticity of muscle.

2.4. The Calculation of Muscle Stretching Force
The stretching process of Hill muscle model is to activate the muscle, which can produce muscle stretching force. The muscle stretching muscle is mainly reflected in the active contractile element and passive contractile element. Its expression can be calculated by formula (1)

\[
F_T = F_a + F_b = \sigma \times PCSA[fa(l)fa(v)a(t) + fp(l)]
\]  

where, Fa is the active force of muscle unit, Fb is the passive force of muscle unit, \( \sigma \) is the maximum stress, PCSA is the area of physiological cross section of muscle, fa(l) is the relationship between force and length of active part, fa(v) is the relationship between force and velocity of active part, a(t) is the muscle activation value, fp(l) is the relationship between force and length of passive part.
\[ f_a(l) = e^{-40\frac{x}{x_0} - 0.95} + (\frac{x}{x_0} - 0.95)^2 \] (2)

\[ f_a(v) = 1.6 - 1.6e^{-1.11(-\frac{v}{v_x} + 1)^4 + 0.1(-\frac{v}{v_x} + 1)^2} \] (3)

\[ f_p(l) = 1.3 \cdot \arctan[0.1(\frac{x}{x_0} - 0.22)^{10}] \] (4)

where, x is the total length of muscle and tendon in the stretching process, x0 is the total length of muscle and tendon in the static state, v is the stretching velocity.

\[ F(r) = \sum_{i=1}^{n} F_{Ti} \] (5)

where F(r) is the total force of hip joint, FTi is the muscle strength provided by muscle group i.

3. The Force Control of Intelligent Bridge-Style Movement Rehabilitation Robot

3.1. The Analysis of Auxiliary Force of Bridge-Style Movement Rehabilitation Robot

The control mode of auxiliary mechanism is divided into force control and position control. The auxiliary mechanism can follow the hip height of the bridge-style movement in the position control mode. The contact force between the auxiliary mechanism and the patient’s hip can be adjusted and controlled in the force control mode. The curve of smooth pursuit movement is shown in figure 6.

3.2. The Algorithm of Auxiliary Mechanism

The basic principle of force control mode is to maintain the dynamic balance of patients by quantitatively providing the required force and torque of hip joint in the process of bridge-style movement. Through the force analysis of bridge-style movement, it can be known that the driving force is provided by the shoulder joint and ankle joint. The bridge-style movement is divided into rotating parts, which can produce the corresponding angular acceleration. The force and torque are divided into the force F foot and torque M foot of ankle joint, the force F thigh and F waist and torque M hip of hip joint, the force F shoulder of shoulder joint, and self-gravity Fg as shown in figure 7.

If the force and torque at the joint and the kinematic parameters of bridge-style movement are known, the balance of human body is ensured by applying external force. The applied external force is the auxiliary force provided by the auxiliary mechanism, which applies on the hip joint. The variables and parameters in the equation can be determined by the sensors and skeletal muscle model. And then, the auxiliary force can be calculated by the equation.

According to Newton’s second law, the balance equation of force and torque at each moment should
be satisfied in the bridge-style movement. These equations are the combination of human active force and robot auxiliary force. The balance equation of force and torque can be calculated by equations (6) and (7):

\[
F_{\text{foot}} + F_{\text{shoulder}} + F_{\text{d}} + F_{\text{auxiliary}} + F_{\text{thigh}} \cdot \cos \alpha_2 + F_{\text{waist}} \cdot \cos \alpha_2 = ma
\]

(6)

\[
F_{\text{foot}} \cdot l_3 + F_{\text{thigh}} \cdot l_2 + F_{\text{waist}} \cdot l_1 + F_{\text{shoulder}} \cdot l_1 + M_{\text{foot}} + M_{\text{knee}} + M_{\text{hip}} = I(\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \alpha_4)
\]

(7)

where, a is the acceleration, 11, 12, 13 is the length between the centroid and shoulder joint, knee joint and ankle, respectively. m is the quality, I is the square root inertia.

3.3. The Simulation Analysis of Auxiliary Force and Speed

The active force produced by patients can be evaluated by the force at the hip joint. Therefore, it is necessary to compare the force and torque of the hip joint. Different K and C were used to simulate different conditions of patients, so that the patients could be better assisted in bridge-style movement.

It can get the different auxiliary force by adjusting the k as shown in figure 8. When the patients’ condition is serious, it means that the patients’ muscle tension is relatively large, so we know that K is larger, which produces the large auxiliary force via auxiliary mechanism. When the patient’s condition is mild, the patients’ can rely on their own initiative to complete the partial bridge-style movement. We know that K is small, which produce small auxiliary force via auxiliary mechanism and assist the patients to complete the standard bridge-style movement.

Parameter C can also be adjusted by the patient’s condition as shown in figure 9. When the patients’ condition is serious, parameter C can adjust to small, which assists patients to complete bridge-style movement at a slower speed. When the patients’ condition is mild, parameter C can adjust to large, which assists patients to complete bridge-style movement at a faster speed.

3.4. The Simulation Analysis Between Force Control and Position Control

When the contact force between the hip and auxiliary mechanism is 0, it means that the human body has left the auxiliary mechanism. At this time, the switch of auxiliary mechanism needs to be turned off to track bridge-style movement, which ensures patients to complete independently without auxiliary mechanism. When the contact force between the hip and auxiliary mechanism is not 0, the auxiliary switch is turned on and help human body complete bridge-style movement. The simulation analysis between force control and position control as shown in figure 10.

![Figure 8. The simulation analysis of auxiliary force.](image)

![Figure 9. The simulation analysis of velocity.](image)
4. Discussion and Conclusion
The rehabilitation robot plays an important role in the current clinical treatment. Thus, this paper proposed an intelligent bridge-style movement rehabilitation robot, which can assist patients to complete bridge-style movement. The auxiliary force is determined by the muscle stretching force. The mode of the auxiliary force is adjusted by different muscle parameters according to the different conditions, which can improve the ability to actively participate in rehabilitation training. And the smooth pursuit movement, auxiliary force and auxiliary velocity of auxiliary mechanism can be verified by system simulation. The results provided that the auxiliary mechanism can be a good assistant in bridge-style movement.

Nonetheless, the auxiliary mechanism proposed in this paper also has partially defects. (1) The bridge-style movement only considers the sagittal motion, and ignores the motion in other directions. (2) The parameters K and C of skeletal muscle are considered in the ideal conditions, and the actual motion state of patients are not explored.

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