Establishment and Simulation of the Damping Torque Model of Hydraulic Intelligent Knee Prosthesis

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Abstract: The intelligent knee prosthesis structure was designed and the dynamics model of the lower limb prosthesis system and hydraulic damper model were established in this paper. The flow area which adjusted the damping torque was identified through the combination of hydraulic damper model and dynamics model. The comparable analysis was done based on the Matlab simulation of damping torque curve with theoretical curve. The damper opening of the specific speed was determined. The trend of the knee joint moment curve produced by the hydraulic damper is consistent with the theoretical moment curve under different flow areas. The damping moment of hydraulic knee joint can be controlled by adjusting the flow area. The proposed damping torque model can provide effective guidance for the determination of the flow area and have important consequences for adjustment of damping torque. Providing theoretical model of the damping torque control for the hydraulic intelligent knee prosthesis.

1 INTRODUCTION

Human gait can be divided into two periodic repeating phases: stance phase and swing phase. The function of the above-knee prosthesis is to maintain the stability of the knee in the stance phase and provide essential damping in the swing phase (Kun Shang, et al., 2009). Therefore, prosthetic knee joint is the most important and complex component of the above-knee prosthesis. Knee torque limits whether the maximum knee flexion is close to the physiological gait. And it determines whether the shank can decelerate smoothly until knee fully extend and the magnitude of the ground impact when the heel strikes the ground. Inappropriate knee torque control will lead to abnormal gait, reduce gait symmetry, and increase energy consumption of the wearer (Chunxia Zhao et al., 2015). The control of knee joint moment can be divided into three kinds: constant friction, mechanical spring and damper control. The control mechanism is that the moment curve generated at the knee joint is close to the moment curve under the physiological gait, so that the shank swing is close to the physiological gait (Yanli Geng et al., 2013). According to whether the knee joint can produce active moment, the knee prosthesis can be divided into active prosthesis and passive prosthesis. Passive knee prosthesis uses pneumatic pressure, hydraulic pressure, magnetorheological and other dampers to generate damping torque, while active knee prosthesis generates active torque through motor, pneumatic muscle, micro hydraulic pump and so on. Intelligent knee joint refers to the application of microcomputer technology and intelligent control technology to the control of knee joint damper, so that the knee joint torque can be automatically adjusted with the change of walking speed and joint angle in order to make the gait symmetry and tracking more closely to healthy people (Tengyu Zhang et al., 2016).

The control of knee torque is always the importance and difficulty of research. Dundass studied the effect of degradation of the hydraulic damper on a patient's gait. In order to eliminate the influence of variables on gait in the gait experiment, a dynamic model was established based on the gait data of patients in the experiment. The ground reaction force predicted by this dynamic model is consistent with the experimental data. However, the drawback is that the model is only for one experimental patient, and it is not universal (Dundass et al., 2003). Furse improves the control

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performance of swing phase torque by adding two series springs to the friction brake single-axis passive knee prosthesis, but it is difficult to apply to the intelligent knee prosthesis with hydraulic and pneumatic control (Furse et al., 2011). Based on the concept of energy flow in human gait, Unal proposed the passive control mechanism of reducing energy consumption of swing phase by using three elastic energy storage elements (Unal et al., 2010). Dabiri designed a passive hydraulic damping controller for swing phase of uniaxial knee prosthesis, but the experimental results show that the maximum flexion angle controlled by the damper is quite different from that of normal people, and the control effect is not ideal (Dabiri et al., 2009). Tahani and Karimi proposed a dynamic model of lower limb prosthesis based on torsion spring control, and optimized the control parameters of swing phase motion (Tahani et al., 2010). Suzuki optimized the dynamics of the musculoskeletal model of the stump to obtain the friction value of the passive knee prosthesis and minimize the energy consumption of the swing muscle (Suzuki, 2010). Based on the control parameters of nonlinear hydraulic damper, Hongliu Yu proposed a dynamic model of swing phase for intelligent lower limb prosthesis, and the dynamic relationship between the opening of damper needle valve and the velocity of swing phase is identified. But this research model think the velocity of damper piston is constant, and it is different from the actual piston velocity (Hongliu Yu et al., 2010).

Domestic and foreign researchers have proved the feasibility of the application of damper in the torque control of knee prosthesis. However, there are still relatively few studies on the design of appropriate intelligent knee prosthesis structure, the construction of dynamic model of the complete system composed of knee damper and stump, and the evaluation of the torque control performance of intelligent knee prosthesis. This study designs a kind of intelligent knee prosthesis with hydraulic damper and establishes the dynamic model of the lower limb prosthesis system and the coupled hydraulic damper damping torque model. In this study, the torque control of the knee prosthesis of the dynamic model is simulated by Matlab, and the effectiveness of the damping torque model and the rationality of the designed intelligent knee prosthesis hydraulic damper structure are proved.

2 MATERIAL AND METHODS

The function of the knee prosthesis is to maintain stability in the stance phase and provide proper damping in the swing phase. At present, the damper used in intelligent knee prosthesis is mainly hydraulic control, pneumatic control, magnetorheological control and hydraulic and pneumatic hybrid control. Pneumatic damping is small. So it is difficult to guarantee the stability of the stance phase and commonly used in multi-axis knee prosthesis. Magnetorheological fluid damper changes the magnetic field intensity and the viscosity of fluid by changing the current, so the damping force at the knee prosthesis is changed to control the moment of knee prosthesis. But the control mechanism of magnetorheological fluid viscosity changes still need to be researched. In addition, it cannot be close to places with strong magnetic and electric fields, which limits the range of use. Hydraulic damper can provide strong damping when the volume is small, which can effectively ensure the stability of the stance phase. So it is mostly used for uniaxial knee prosthesis (Wujing Cao et al., 2016).

2.1 Structural Design of Knee Prosthesis

Hydraulic damping force presents different properties with the change of hydraulic fluid velocity. When the flow velocity is slow, the damping and velocity are linear, that is, the damping is proportional to the flow velocity. When the velocity is large, the increase of damping is nonlinear, that is, damping is proportional to the

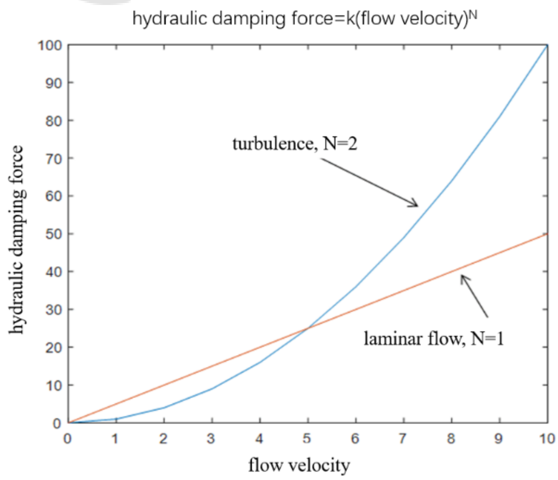

Figure 1. Relation of flow speed and damping force.

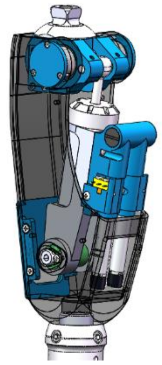

Figure 2. Knee prosthesis structure.

square of velocity (Staros & Murphy, 2013). When the hydraulic oil flows through the small hole in the circular tube in laminar flow state, the flow velocity will increase instantly due to the sudden decrease of flow area, resulting in turbulence. The relationship between hydraulic damping force and flow velocity change is shown in Fig. 1. This property makes it possible to adjust the damping force of knee joint at different speeds by changing the flow area of hydraulic fluid. And then it changes the velocity of hydraulic oil to create turbulence to achieve rapid adaptation and control of damping torque. This is very beneficial to the acquisition of the physiological gait of the knee swing phase. Therefore, uniaxial hydraulic knee joint structure is selected (Hongliu Yu et al., 2009). In order to realize the independence of intelligent knee flexion and extension damping torque control, two motors are used to control the corresponding plug valve respectively. The flow area of the oil passage is changed by the DC motor rotating plug valve, so that the flow rate of the hydraulic oil is instantaneously increased to form turbulent flow and cause pressure loss. And then it controls the pressure difference between the upper and lower chambers to generate the damping force so as to achieve the control of the knee damping torque at different speeds. The overall knee structure is shown in Figure 2. In order to ensure that the damping of the flexion oil passage and the extension oil passage do not affect each other, a check valve is placed in each of the two oil passages. When the knee is flexed and the hydraulic piston moves downward, the check valve in the extension oil passage is closed and the check valve in the flexion oil passage is opened. And then the hydraulic oil can only enter the upper chamber from the lower chamber through the flexion adjustment oil passage. When the knee is extended and the hydraulic piston moves upward, the check valve in the flexion oil passage is closed and the check valve in the extension oil passage is opened. And then the hydraulic oil can only enter the lower chamber from the upper chamber through the extension adjustment oil passage. In order to assist the knee extension, a spring is placed in the bottom of the hydraulic cylinder. In each phase state, the opening of the hydraulic damper valve is controlled to adjust the flow rate of the hydraulic oil and then control the knee damping torque. The magnitude of the damping torque is proportional to the square of the knee angular velocity.

$$M = CV^2 \tag{1}$$

M is the knee damping torque, V is the knee angular velocity obtained by deriving the knee angle signal, and C is the knee dynamic damping constant. Five valve opening degrees, namely five different damping constant values, are controlled during a given walking cycle to achieve five phase adaptations and adjustments. The damping value is adjusted only when the gait phase transforms or the period changes, and the damping constant is not adjusted within a certain gait phase. The purpose of the intelligent knee prosthesis adaptive control system is to determine the damping constant which is adapted to the phase state, that is, to control the appropriate valve opening when the state transforms, and then the physiological gait is achieved.

2.2 Dynamic Modeling of Lower Limb Prosthetic System

The uniaxial knee prosthesis is connected to the wearer's thigh stump through the prosthetic socket. In order to design the knee controller, the thigh motion experimental data is provided to the system dynamics model to obtain the expected knee damping torque curve. The damping torque curve actually provided by the hydraulic damper is obtained by adjusting the flow area of the hydraulic damper in Matlab. The difference between the simulation curve and the theoretical curve is analyzed and compared, and the optimal flow area of the hydraulic damper at different speeds is obtained. The dynamic model is validated to provide theoretical guidance for the control of the knee joint damping torque.

The dynamic model of incorporating the hydraulic damper into the lower limb prosthetic system is shown in Fig. 3. The lower limb prosthetic system of the amputated patient can be simplified

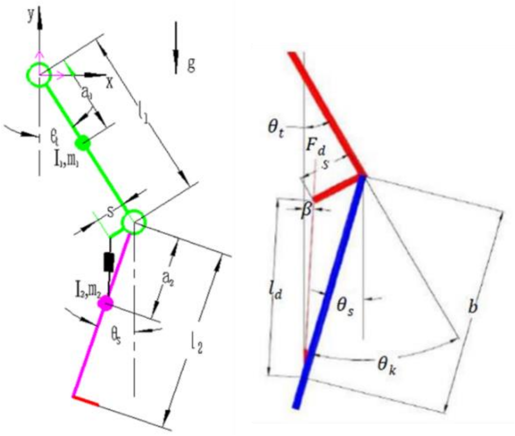

Figure 3. Dynamics model of lower limb prosthesis.

into a two rigid body model, which represents the movement of the thigh and the calf in the sagittal plane. The foot and leg tube are equivalent to a rigid connection. In Fig. 3, subscripts 1 and 2 represent the thigh and calf parameters respectively. m_i represents the mass. a_i represents the distance from the centre of mass to the rotating joint. I_i represents the rotational inertia. θ_t and θ_s represent the angle between the thigh and the calf and the vertical direction, respectively. θ_k represents the knee angle. l_d represents the length of the damper. s represents the distance between the centre of knee rotation and the connection point on the piston rod of the hydraulic damper. b represents the distance between the centre of knee rotation and the joint point of the damper under the leg tube. T_1 represents hip torque.

Assuming that there is no friction between joints, the second type of Lagrange equation is used to establish the dynamic model (Xiaodong Wang et al., 2015).

$$D(\theta)\ddot{\theta}+C(\theta,\dot{\theta})+G(\theta)=\Gamma \tag{2}$$

Inertial matrix is given by

$$D(\theta)=\begin{bmatrix} m_1a_1^2+I_1+m_2l_1^2 & -m_2l_1a_2\cos(\theta_t+\theta_s) \\ -m_2l_1a_2\cos(\theta_t+\theta_s) & m_2a_2^2+I_2 \end{bmatrix} \tag{3}$$

Coriolis force and centrifugal force influence coefficient matrix is given by

$$C(\theta,\dot{\theta})=\begin{bmatrix} m_2l_1a_2(\dot{\theta}_s)^2\sin(\theta_t+\theta_s) \\ m_2l_1a_2(\dot{\theta}_t)^2\sin(\theta_t+\theta_s) \end{bmatrix} \tag{4}$$

Gravity torque parameter matrix is given by

$$G(\theta)=\begin{bmatrix} m_1ga_1\sin(\theta_t)+m_2gl_1\sin(\theta_t) \\ m_2ga_2\sin(\theta_s) \end{bmatrix} \tag{5}$$

Hip and knee parameter matrix is given by

$$\Gamma=\begin{bmatrix} T_1+F_db\sin(\theta_s-\beta) \\ -F_db\sin(\theta_s-\beta) \end{bmatrix} \tag{6}$$

Thigh and calf angle vector matrix is given by

$$\theta=\begin{bmatrix} \theta_t \\ \theta_s \end{bmatrix} \tag{7}$$

In the calculation of the dynamic equation of lower limb movement, the hip torque and the thigh angle produced by a normal person are known inputs. Knee torque determined by Lagrange equation can be expressed as follows:

$$\begin{aligned} M_k' &= m_2a_2^2\ddot{\theta}_s - m_2l_1a_2\ddot{\theta}_t\cos(\theta_t+\theta_s) \\ &+ m_2l_1a_2\dot{\theta}_t^2\sin(\theta_t+\theta_s)+I_2\ddot{\theta}_s+m_2ga_2\sin\theta_s \end{aligned} \tag{8}$$

2.3 Hydraulic Damper Model

The hydraulic damper is a spring damper system. It generates a real-time varying damping torque when the knee prosthesis moves, so that the maximum angle of the knee can be controlled at different speeds to achieve physiological gait (Siyuan Gong et al., 2010). The change of the hydraulic damping torque is achieved by adjusting the opening of the damper valve. The knee damping torque actually generated by the hydraulic damper is given byx

$$M_k=(F_d+k\Delta x)\mathrm{L} \tag{9}$$

k is extension spring modulus, and Δx is spring compression. Real-time moment arm length can be expressed as follows:

$$L=\frac{bs\cos(\theta_s-\theta_t)}{\sqrt{b^2+s^2+2bs\sin(\theta_s-\theta_t)}} \tag{10}$$

Hydraulic damper pressure difference between upper and lower chamber is ΔP, and the effective action area of the piston is A. Hydraulic damping force can be expressed as follows:

$$F_d=\Delta PA \tag{11}$$

Damper piston velocity is V. When hydraulic oil flows through the valve, the effective flow area is A_0. Flow coefficient is C_d. And Hydraulic oil density is ρ. So ΔP can be expressed as follows:

$$\Delta P=\frac{\rho A^2V^2}{2C_d^2A_0^2} \tag{12}$$

The length of the damper l_d is a variable during the movement. It can be expressed as follows:

$$l_d=\sqrt{b^2+s^2+2bs\sin(\theta_s-\theta_t)} \tag{13}$$

Damper piston velocity is given by

$$V=\dot{l}_d=\frac{bs\cos(\theta_s-\theta_t)(\dot{\theta}_s-\dot{\theta}_t)}{\sqrt{b^2+s^2+2bs\sin(\theta_s-\theta_t)}} \tag{14}$$

So the knee damping torque actually generated by the hydraulic damper is given by

$$M_k=\left(\frac{\rho A^3V^2}{2C_d^2A_0^2}+k\Delta x\right)\frac{bs\cos(\theta_s-\theta_t)}{\sqrt{b^2+s^2+2bs\sin(\theta_s-\theta_t)}} \tag{15}$$

And then the knee damping torque actually generated by the hydraulic damper can be expressed as follows:

$$M_k=\left(\frac{\rho A^3b^2s^2\cos^2(\theta_s-\theta_t).(\dot{\theta}_s-\dot{\theta}_t)^2}{2C_d^2A_0^2(b^2+s^2+2bs\sin(\theta_s-\theta_t))}+k\Delta x\right)\frac{bs\cos(\theta_s-\theta_t)}{\sqrt{b^2+s^2+2bs\sin(\theta_s-\theta_t)}} \tag{16}$$

Coupling the knee torque determined by the kinetic equation with the torque provided by the hydraulic damper is given by

$$M_k=M_k' \tag{17}$$

When the knee geometric parameters and human body parameters are determined, the hip and knee angle information are measured and the real-time valve flow area can be obtained. However, due to the short time of a gait cycle, if the motor is used to drive the valve to make the real-time change of the area completely and track the matching theoretical torque curve in actual operation, speed adjustment will be too late and power consumption will be fast. Therefore, the following simulation simulates the actual torque curve and the theoretical torque curve generated by several fixed flow areas at a walking speed, and compares the analysis curve to determine the most suitable flow area at this speed. The area data is stored. And when the sensor detects the walking speed of the wearer, the stored data can be directly called.

2.4 Damper Torque Simulation

Using the hip and knee angle information of a healthy person at a walking speed, the damping torque curve required by the Lagrangian equation is obtained by Matlab. The damping torque curve actually provided by the hydraulic cylinder is obtained by Matlab under the same conditions different flow conditions, and then the best flow area A_0 under this walking speed is obtained. In this way, the optimal flow area under different walking speeds is obtained in turn. The parameters of the lower limb prosthesis system are designed as follows:

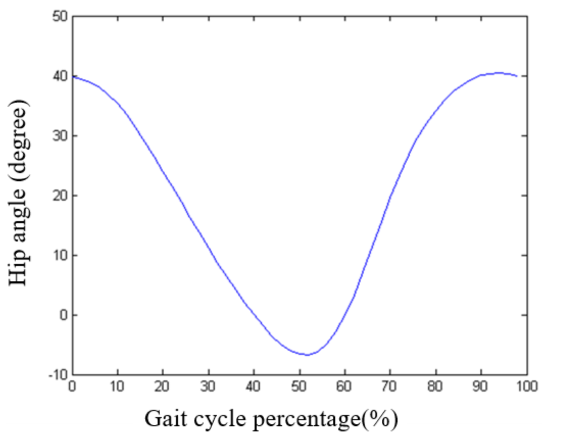

Figure 4. Hip angle input.

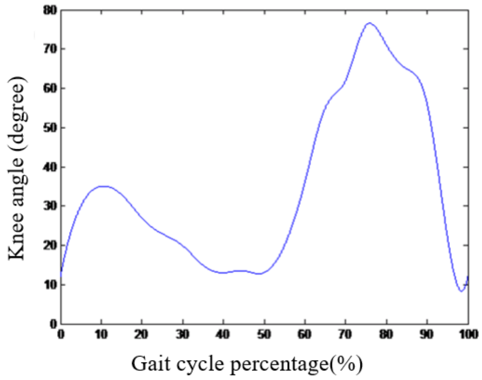

Figure 5. Knee angle input.

$m_1 = 9.9kg$, $m_2 = 2.6kg$, $l_1 = 0.55m$, $l_2 = 0.4m$, $a_1 = 0.267m$, $a_2 = 0.176m$, $I_1 = 0.031kg.m^2$, $I_2 = 0.0032kg.m^2$, $\rho = 870kg/m^3$, $A = 5.37\times10^{-4}m^2$, $b = 0.185m$, $s = 0.02m$, $C_d = 0.7$, $k = 1.4\times10^3 N/m$. The walking experimental data of the normal person was obtained from the literature (Matinmanesh & Mallakzadeh, 2011). And the hip angle curve and the knee angle curve are shown in Fig. 4 and Fig. 5, respectively.

The theoretical calculation of the knee joint torque curve and the flow area A_0 are respectively taken $0.8\times10^{-5}m^2$, $1.3\times10^{-5}m^2$, $1.9\times10^{-5}m^2$, and the hydraulic damper actually provides the torque curve as shown in Fig. 6.

It can be seen from the figure that under different flow areas, the overall trend of the

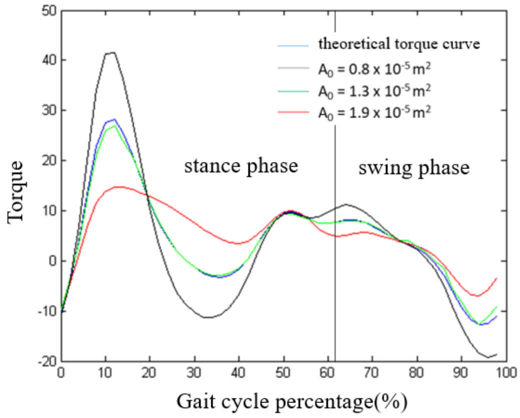

Figure 6. Knee theoretical torque and damping torque in different flow area.

hydraulic damping torque curve is consistent with the theoretical torque curve. When A_0 is $1.3\times10^{-5}m^2$, the simulated knee torque is closest to the theoretical torque curve. So this flow area can be used as a preset flow area at this speed.

3 DISCUSSION

The torque required for the knee prosthesis at different speeds are different. The control of the knee damping torque is realized by the damper to realize the tracking speed of the wearer. The adjustment of the hydraulic knee damping force is achieved by changing the flow area of the upper and lower chambers of the hydraulic cylinder, and the specific traveling speed corresponds to a specific optimal flow area. As the flow area increases, the damping force decreases nonlinearly. And when the walking speed is constant, there is always a corresponding optimal flow area. The theoretical simulation results verify the correctness of the kinetic model for knee damping torque control. Since the modeling parameters are taken from healthy people, the actual application will inevitably produce a certain deviation. For specific lower limb amputation patients, data from healthy people with similar body size can be used as initial data for prosthetic wearers. After the prosthesis is worn, the angle information of the wearer's healthy leg and the knee parameters are recalculated to obtain an optimized opening degree.

4 CONCLUSIONS

In this study, a dynamic model of the lower limb prosthetic system was established by designing an intelligent knee joint structure. The coupling of the hydraulic damper and the system dynamics model is used to determine the flow area of the knee damping torque. The Matlab-based simulated damping torque curve is compared with the theoretical curve to determine the knee damper opening at the tester's specific speed. The following results are obtained from the simulation:

(1) The relationship between hydraulic damping and flow rate determines its superiority for knee joint damping torque control. The hydraulic damping torque curve can be obtained by changing the flow area of the valve. By comparing and analyzing the theoretical knee torque curve and the hydraulic damping torque curve, the optimal flow area at a specific speed can be obtained.

(2) As the flow area increases, the knee joint damping torque gradually decreases. The optimal flow area at different speeds can be simulated multiple times by using the measured hip and knee angle curves as input data.

(3) The knee damping torque curve under the optimal flow area obtained by the simulation has a small deviation from the theoretical curve, but the change trend is basically consistent with the theoretical curve. The correctness of the kinetic model is verified and can be optimized by replacing the data of healthy people with the wearer's own measured data.

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