Research the Gait Characteristics of Human Walking Based on a Robot Model and Experiment

H J He¹, D N Zhang¹, Z W Yin² and J H Shi¹

¹The 21st research institute of China electronics technology group corporation, Shanghai 200230, China
²Institute of Precise Forming and Knowledge Based Engineering of Shanghai Jiaotong University, Shanghai 200030, China
jevls@163.com

Abstract. In order to research the gait characteristics of human walking in different walking ways, a robot model with a single degree of freedom is put up in this paper. The system control models of the robot are established through Matlab/Simulink toolbox. The gait characteristics of straight, uphill, turning, up the stairs, down the stairs up and down are analyzed by the system control models. To verify the correctness of the theoretical analysis, an experiment was carried out. The comparison between theoretical results and experimental results shows that theoretical results are better agreement with the experimental ones. Analyze the reasons leading to amplitude error and phase error and give the improved methods. The robot model and experimental ways can provide foundation to further research the various gait characteristics of the exoskeleton robot.

1. Introduction

In recent years, there are some foreign institute carrying out studying the gait training, such as Gait Simulator in Japan [1-2], LOKOMAT in Switzerland and Hapticwalker in Germany. A 6-DOF robot integrating biological, technologies of robot, and virtual reality is designed for gait training by researchers in Makikawa laboratory in Ritsumeikan University of Japan, which could do trainings of straight, uphill, downhill, up the stairs, down the stairs and turning.

A rehabilitation robot was named as LOKOMAT and its exoskeleton is only applied to some training such as running and walking because its structure was based on treadmill, which was structured by the Swiss Federal Institute of Technology Switzerland [3].

Another kind of 6-DOF robot named as Hapticwalker for gait training (Hapticwalker) had the characteristics of exoskeleton and treadmill and was researched by Charite Hospital and Fraunhofer
IPK in Berlin in Germany. Patients can use Hapticwalker to do on-line gait analysis and the pathological data offered can evaluate the effect of rehabilitation under the help of biofeedback. Hapticwalker adopted a variety of control methods which included compliance control and position control [4-5]. Above control methods were applied to different patients. For example, if some patients were more serious illness, the compliance control will be better suitable for them to do passive exercise. But if the patients were less serious illness, position control will be suitable for them to do simple exercise such as straight, uphill, downhill, up the stairs and down the stairs. The researchers proposed that different environment should be simulated for Hapticwalker such as hard pavement and soft sand [6-7].

In addition to above research, many other colleges and institutes in Japan, Russia, the U.K., German, Korea and Singapore also started their own projects [8]. At present there have been few researches on robot combining experiment and theoretical simulation.

Therefore, a theoretical model of the gait training robot is given based on its structure in this paper. The characteristics of gaint were analyzed, and a compliance control strategy is proposed for the theoretical model. With MATLAB/Simulink toolbox, the system control models are established and the simulation is carried out in the second part. An experiment is designed and introduced in the third part. In fourth part, there is a comparison between simulation result and experimental result. Finally, there is a conclusion and outlook.

2 Simulation Model

2.1 Structure of robot

Figure 1 shows a single DOF exoskeleton platform. If a wear swings his lower limb under the help of predefined motion, the wearer’s lower limb will meet closely to the single DOF exoskeleton in this platform. In this structure, the left leg of exoskeleton is designed as a rigid link pivoting, so the knee joint is a rotational one for which a DC servo motor provides power. The actuator torque $\tau_a$ is produced through DC motor about point $O$. Finally, the total equivalent torque is expressed as the torque $\tau_h$ about the point $O$. The dynamic equation of wear’s lower limb of exoskeleton can be shown as,

$$
(I_e + I_a) \frac{d^2 \theta_e(t)}{dt^2} + (D_e + D_a) \frac{d\theta_e(t)}{dt} + (M_e l_e + M_a l_a) \sin \theta_e(t) + C_a \text{sign}(\frac{d\theta_e(t)}{dt}) = \tau_a(t) + \tau_h(t)
$$

(1)

Where $l$, $M$, $D$ and $I$ respectively represent viscous friction coefficient, lower thigh mass, length and lower thigh inertia, viscous friction coefficient and inertial moment of the exoskeleton, $C_a$ is friction coefficient about the knee joint of the exoskeleton robot. Figure 2 (a) explains a master-slave model of the system.
Figure 1. A prototype of lower exoskeleton with the for human enhancement motion

Figure 2. (a) A single DOF exoskeleton interacting wearer’s lower thigh during swinging motion

2.2 Description of interaction resulting from human

Table 1. Nonlinear mapping models of the resulting interaction torque from human. The factors M, B, K are expressed as time varying ones

| Case | Mapping model | Example |
|------|---------------|---------|
| $f_1$ | $\tau_{\text{int}} = f(\theta_h, \theta_z)$ | $\tau_{\text{int}} = K(\theta_h - \theta_z)$ |
| $f_2$ | $\tau_{\text{int}} = f(\theta_h, \dot{\theta}_h, \theta_z, \dot{\theta}_z)$ | $\tau_{\text{int}} = M\dot{\theta}_h + B\dot{\theta}_z + K(\theta_h - \theta_z)$ |
| $f_3$ | $\tau_{\text{int}} = f(\theta_h, \dot{\theta}_h, \dot{\theta}_z)$ | $\tau_{\text{int}} = B(\dot{\theta}_h - \dot{\theta}_z) + K(\theta_h - \theta_z)$ |
| $f_4$ | $\tau_{\text{int}} = f(\theta_h, \dot{\theta}_h, \dot{\theta}_z, \theta_z, \dot{\theta}_z)$ | $\tau_{\text{int}} = -M(\ddot{\theta}_h - \ddot{\theta}_z) + N(\dot{\theta}_h - \dot{\theta}_z) + K(\theta_h - \theta_z)$ |

There is an important issue that the torque $\tau_H$ is how to describe the characteristics of the interaction resulting from human. Generally, the $\tau_H$ can be described by the active torque $\tau_{\text{act}}$ from wearer’s muscle torque and the torque $\tau_{\text{int}}$. The $\tau_H$ can be expressed by a function of dynamic factors showing the human-robot structure during motion:

$$\tau_H(t) = \tau_{\text{act}} + \tau_{\text{int}}$$

Where, the active torque $\tau_{\text{act}}$ is dependent on the wearer central nervous system and $\tau_{\text{act}}$ is general considered as a kind of impact torque in a moment. When the impact torque is generated, the relationship between $\tau_H$ and the dynamic variables $\theta_n, \dot{\theta}_n, \ddot{\theta}_n, \theta_s, \dot{\theta}_s, \ddot{\theta}_s$ can be constructed by the interpretation of regression technique. Most of research, the environment-robot interaction is shown as many models of dynamic variables and geometric constraints. Through above models proposed in literature. The most typical model will be considered as expressed in Table 1.

2.3 Nonparametric regression techniques

Through above discussion, parameter and structure of $\tau_H$ are difficult to define explicitly. Hence, regression techniques are particularly used for this kind of regression problems. In this paper, nonparametric regression method is adopted to describe the relationship of the interaction through the dynamic variables. Gaussian Process Regression is the most standard method because of competitive performance. It has a disadvantage that Gaussian Process Regression needs a high computation cost.
Locally Weighted Projection Regression is thought as the ability of fast computation. Gaussian Process Regression is based on Gaussian model that is explained by its covariance function and mean function in detail. It is estimated by a linear model:

\[ f(x) = \psi(x)^T \omega, \quad y = f(x) + \xi \]  

(3)

Where the weight vector is \( \omega \), the input vector is \( x \), and additive noise is \( \xi \) that is independent Gaussian distribution including variance \( \sigma_n \) and zero mean. With respect to linear equation (3), the regression problem is simplified as using various kernel functions such as Gaussian kernel and others.

\[ y \] is called as likelihood. According to the given parameters \( \psi(x) \) and \( \omega \) can be written as:

\[ p(y|\phi, \omega) \propto e^{-\frac{1}{2\sigma_n^2} \phi^T \sigma_n^{-2} \phi} = N(\phi^T \omega, \sigma_n^2 I) \]  

(4)

The probability density of \( \omega \) is given by:

\[ p(\omega) \propto e^{-\frac{1}{2} \omega^T \sigma_n^{-2} \omega} = N(0, \sigma_n^{-2}) \]  

(5)

The probability density of the weights is given inputs and targets are proportional based on Bayes’ rule:

\[ p(\omega) \propto e^{-\frac{1}{2}(\omega-\nu)^T \sigma_n^{-2} (\omega-\nu)} = N(\nu, \sigma_n^{-2} A^{-1}), \quad A = \sigma_n^{-2} \phi \phi^T + \sum_{p}^{n} \nu = \sigma_n^{-2} A^{-1} \phi y \]  

(6)

To predict the next input \( x_p \), the \( f_p \) and \( V_p \) can be written as follow:

\[ \bar{f}_p = k_p^T (K + 2\sigma_n^2 I)^{-1} y = k_p^T \xi, \quad V_p = k(x_p, x_p) - k_p^T (K, \sigma_n^2 I)^{-1} k_p \]  

(7)

\( k_p, k(x_p, x_p) \) and \( k \) can be expressed as:

\[ k_p = \psi_p^T \sum_p \phi, \quad k(x_p, x_p) = \psi_p^T \sum_p \psi_p, \quad K = \phi^T \sum_p \phi \]  

(8)

It is known that the predicted value are respectively obtained by \( f_p \) and \( V_p \). The vector \( \xi \) can be predicted and computed during every training.

3. Introduction of Experiment

An exoskeleton experimental platform has been designed and built for finishing the experiments with various walking ways such as straight, uphill, turning, up the stairs, down the stairs and up and down. The structure design and hardware configuration of the experimental platform are shown in Figure 3. This paper adopted the experimental platform and used the motion of the lower thigh as a scaled-down model of the swing leg in walking cycles. The influence of dynamic variables on the resulting interaction torque can be estimated.

As shown in Figure 3, the structure of the exoskeleton platform is constituted by a DC servo motor with a customized harmonic gearbox, a stationary frame and an exoskeleton arm.
The motor has an incremental optical encoder of a resolution of 2000 counts per revolution that allows the measurement of the joint angle of the exoskeleton arm. In order to reduce the weight and inertia, the arm of the exoskeleton is made of aluminum. An inclinometer is built that is attached to the wearer’s lower limb to measure the angular position of wearer’s shank relative to gravity. A three-axis angular rate sensor which is named as L3G4200D and a three-axis accelerometer with high resolution (14 bit) is named as ADXL345 are adopted in this exoskeleton experimental platform. Besides, in order to measure the active torque from the wearer, the torque sensor is applied. It is installed between the rotating arm and the motor’s shaft. To reduce the influence of error from using numerical differentiation method on the calculation of angular accelerations, digital inertial measurement units were applied to the exoskeleton and human to attenuate uncertainties occurred in the motion data.

An embedded control system is researched and designed, which increases the ability of integration, realizes the main controller to interchange information with distributed sensors favorably and ensure real-time control performance in our exoskeleton-human system laboratory. In this paper, the one DOF experimental platform is designed and its hardware configuration designed was used as a part of the whole distributed embedded system.

The hardware system is constituted by Elmo’s digital servo drive for driving the DC motor, a personal computer (PC) for developing a graphical user interface and executing the online learning procedure, and a 120 MHz STM32F microcontroller as the main computational module with respect to this platform.

The message of sensor is input by the microcontroller to the microcontroller which sends appropriately computed control signals to the driver.

The communication mode is Controller Area Network CAN1 to offer a consistent and understandable behavior and visual data. The controller via CAN network (CAN2) is adopted to communicate for the Elmo drive. The general embedded system framework of the platform is shown in Figure 4.

The safe factor of the mechanical structure and the controller should be considered when the experiments are related to human motion.

4. Analysis of Theory and Experiment
4.1 Comparison between theoretical results and experimental results

According to the above description of experiment, two persons attached with the exoskeleton perform swinging motion and the robot is controlled by a PD master-slave control. They are healthy people whose weights were 72 kg (first person) and 64.5 kg (second person). The wearers are instructed to swing their shank according to bounded sinusoidal trajectories. In order to collect data, the wearers wear the exoskeleton at the foot bracket and the inclinometer and the acceleration sensor is properly fixed at their lower thigh simultaneously. It is known that each collected data set is constituted by six inputs. From above discussion, each collected data set consists of six inputs \( \phi = (\theta_h, \dot{\theta}_h, \ddot{\theta}_h, \theta_e, \dot{\theta}_e, \ddot{\theta}_e) \) and one output \( [\tau_{int}] \). A user interface is designed to store and display the collected data for every wearer on the PC.

The experiment of gait training is measured ten times for straight, uphill, turning, up the stairs, down the stairs and up and down, and the relationship can be evaluated under the same conditions for every wearer.

![Figure 5](image)

**Figure 5.** (a) the comparison between theoretical results and experimental results about walking along straight line; (b) the comparison between theoretical results and experimental results about Uphill

The comparison between theoretical result and experimental result of the angular position, angular velocity, angular acceleration, torque and power is respectively shown about walking along straight line in Figure 5 (a) and uphill in Figure 5 (b).

The comparison of angular velocity shows that theoretical result and experimental result have the same changing trend and the maximum amplitude error is smaller. Especially, there is no phase error.

The comparison of angular acceleration shows that theoretical result and experimental result have the same changing trend and the maximum amplitude error is smaller. The phase error is very small.

The comparison of torque shows that theoretical result and experimental result have the same changing trend and the maximum amplitude of theoretical result is larger than experimental ones.

The comparison of power shows that theoretical result and experimental result have the same...
changing trend and the maximum amplitude error is smaller. The phase of theoretical result is the same as the first person.

4.2 Discussion of analysis result

From the comparison between theoretical result and experimental result about different gait training such as walking along straight line, uphill, turning, up stair, down stair and up and down, changing trends of theoretical results are better agreement with experimental results. But the maximum amplitude error and phase error exists in some walking ways.

For example, the comparisons of angular position and power have a phase error and the comparisons of angular acceleration and torque have a maximum amplitude error. There are three reasons leading to amplitude error and phase error as follows:

First of all, the angular rate sensor that is used in experiment platform is not high accuracy and sensitivity. The angular rate sensor is attached with exoskeleton robot. When the wear did training with lower accuracy and sensitivity, the position feedback may be delayed. The final result will lead to phase error between theoretical result and experimental result on angular position and power.

Secondly, different wearer has different angular velocity for gait training. Because the different angular velocity produces different angular acceleration and the best torque, the vibration amplitude may be different. But the theoretical model only describe different wearer basic feature such as weight, height and basic speed, it is difficult accurate to track changing speed of wearers in real time. The final result will lead to amplitude error between theoretical result and experimental result on angular acceleration and torque.

Finally, the experimental platform may be needed to improve in order to improve the accuracy and precision of the experiment. The current experimental device did not fix vibration test sensor so that the vibration signal of gait training did not send the control system. The signal of vibration amplitude may be not evaluated accurately. The final result will lead to amplitude error between theoretical result and experimental result.

Above all, there are many factors leading to amplitude error and phase error, experimental device, wearer’s training ways, sensor, control system and so on. The follow-up work will improve the theoretical model and experimental platform.

5. Conclusion and future work

In order to research the gait characteristics of straight, uphill, turning, up the stairs, down the stairs up and down, a robot model with a single degree of freedom was put up in this paper. The system control models of the robot were established through Matlab/Simulink toolbox. To verify the correctness of the theoretical analysis, an experiment was carried out. The comparison between theoretical result and experimental result about different gait training such as walking along straight line, uphill, turning, up stair, down stair and up and down, changing trends of theoretical results are better agreement with experimental results. Analyze the reasons leading to amplitude error and phase error. The follow-up work will improve the theoretical model and experimental platform. The robot model and experimental ways can provide foundation to further research the various gait characteristics of the exoskeleton robot.
References

[1] TSUJI T, TANAKA Y. Tracking control properties of human-robotic systems based on impedance control[C]//Transactions on Systems, Man and Cybernetics, Part A (Systems & Humans). Hiroshima Hiroshima University Press, 2005: 523-535.

[2] Kazerooni H, Racine J L, Huang L, et al. On the control of the Berkeley Lower Extremity Exoskeleton (BLEEX). In: Proceedings of the IEEE International Conference on Robotics and Automation, Barcelona, 2005. 4353–4360.

[3] HIDLER J M, WALL A E. Alterations in muscle activation patterns during robotic-assisted walking [J]. Clinical Biomechanics, 2005, 20(2): 184-193.

[4] TONG Xiang-qian, SHEN Ming, CHEN Gui-liang. Impedance control characteristic of active reactor [J]. Journal of Xi’an University of Technology, 2007, 23(1): 25-28.

[5] SCHMIDT H, PIORKO F, BERNHARDT R, KRUQER J, HESSE S. Synthesis of perturbations for gait rehabilitation robots [C]// Proceedings of IEEE International Conference on Rehabilitation Robotics. Chicago: IEEE Press, 2005: 74-77.

[6] PATHAK P M, MUKHERJEE A, DASGUPTA A. Impedance control of space robot[J]. International Journal of Modelling and Simulation, 2006, 26(4): 316-322.

[7] HUNT K J, JACK L P, PENNYCOTT A, PERRET C, BAUMBERGER M, KAKEBEEKE T H. Control of work rate-driven exercise facilitates cardiopulmonary training and assessment during robot-assisted gait in incomplete spinal cord injury[J]. Biomedical Signal Processing and Control, 2008, 3(1):19-28.

[8] Tran H-T, et al. Fuzzy-based impedance regulation for control of the coupled human-exoskeleton system. In: Proceedings of the IEEE Conference on Robotics and Biomimetics, Bali, 2014, in press.