Intelligent Control based on Location-Force Model

Jianfeng Sui, Linhong Ji

Department of Mechanical Engineering
Tsinghua University
Room 3403,Building 9003, No.1 Tsinghua Park, Haidian district, Beijing
100084
suijianfeng1986@sina.com
jilh@tsinghua.edu.cn

Abstract: This article introduces a multi-posture locomotor training device (MPLTD)with a closed-loop control scheme based on joint-angle feedback, which is able to overcome varies difficulties resulting from mechanical vibration and the weight of trainer to achieve higher accuracy trajectory. By introducing the force-field control scheme that used in the closed-loop control, the device can obtain the active-constrained mode including the passive one. The MPLTD is mainly composed of three systems: posture adjusting and weight support system, lower limb exoskeleton system, and control system, of which the lower limb exoskeleton system mainly includes the indifferent equilibrium mechanism with two degrees of freedom (DOF) and the driving torque is calculated by the Lagrangian function. In addition, a series of experiments-the weight support and the trajectory accuracy experiment demonstrate a good performance of mechanical structure and the closed-loop control.

1 Introduction of the MPLTD

The MPLTD consists of three systems: posture adjusting and weight support system, lower limb exoskeleton system, and control system. Lower leg exoskeleton length (from knee joint to pelma) is adjustable and the range is 390 ~570 mm, while upper leg exoskeleton length (from hip to knee) is also adjustable and the range was 325~505 mm [FGO12] ; The motion angle range of hip joint (angle between thigh longitudinal axis and neutral position) is 10° ~40° , while the knee joint range (angle between calf longitudinal axis and thigh longitudinal axis) is 0° ~70° [RB13], and the dorsiflexion and plantar flexion of ankle joint is in the normal range.

The lower limb exoskeleton system consists of indifferent equilibrium mechanism, linear motors, bandage, and pedal with gasbag. Inheriting the biological structure of human legs, the main structure of the indifferent equilibrium mechanism is designed based on serial-restraining and parallel-driving principle with two degrees of freedom, see Figure 2, whose structure size meets H/h=L/l. When the angle between the linear guideway and the bed frame is small, the direction of the combine strength of the mechanism's and legs' weight is perpendicular to the linear guideway, so it almost do not need tractive force to make it move, which is the principle of indifferent equilibrium. This mechanism is very suitable for users under active-constrained mode, because users do not have to overcome the gravity of their own lower limb to achieve locomotion training. Linear actuator 2 drives hip joint and actuator 1 drives knee joint, interworking to simulate the gait for users' passive locomotion training.

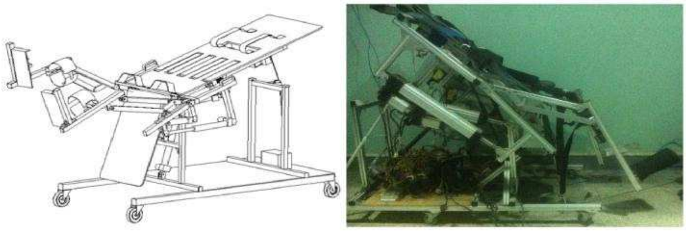

Figure 1: The multi-posture locomotor training device

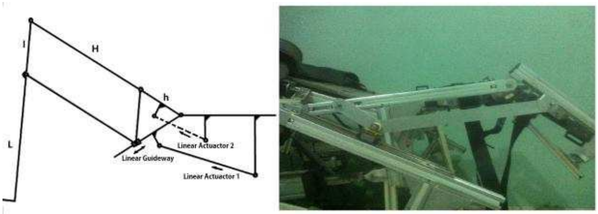

Figure 2: The lower limb exoskeleton schematic diagram

2 Control System Design

In order to obtain the control algorithm using real-time feedback of joints and velocity control of the driven motors, a control system is developed, which includes industrial computer, controller, and sensors. Without feedback controllers design, the open-loop control mode of MPLTD based on the inverse kinematic modeling will have limited control accuracy due to external influences. Owing to the angle sensors, closed-loop control scheme for MPLTD based on feedback is prosed so that the motion control accuracy can be significantly improved. The passive mode and active-constrained mode are achieved by position, velocity and current control. In the passive mode, the control model of the MPLTD relates the joint angle velocities to the time derivative of gait simulation. The target of the control is for the joint angles measured by the encoders installed in the motor tails to approach their desired values; while in the active-constrained mode, torques of these two motors are controlled by current control, which is achieved according to the linear relationship between thrust and electric current within the operating range, and detailed interpretation will be mentioned later.

2.1 Location-Force Model

Active-constrained mode control algorithm is to determine the force $\vec{F}_{t+\Delta t}$ which should be applied to lower extremity (foot) by motors at the next time $t+\Delta t$, according the actual movement of the device end position $(\vec{P}_t, \dot{P}_t)$ at the instant time t, then the control function model is $\vec{F}_{t+\Delta t} = f(\vec{P}_t, \dot{P}_t)$. By changing the control function f, we can get all robotic exoskeletons end force for different positions at any time. Namely, that is, we can achieve different control effect and different force field in the plane. Active-constrained mode can be altered with a range of parameters; including constraint motion preset trajectory length, maximum auxiliary force size, etc., corresponding to $(x_t, y_t) \rightarrow F_{t+\Delta t}$ the different relationship between the position and the formation-force. The following figure (Figure 3) shows the location-force control parameters schematic, reflecting the output force of exoskeleton ends at different positions in a cross-section [Br72] [CBN11].

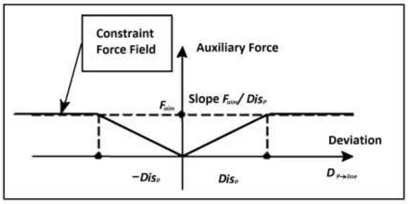

Figure 3: Force field controlling diagram

2.2 Intelligent Control—Active-constrained mode

In the active-constrained mode, if exoskeleton ends run within a set trajectory range, users can drive the lower extremity exoskeleton to do movement in the state of freedom; while exoskeleton ends deviate from the target trajectory, the constraint force field will pull limbs to the target trajectory from the wrong position by the most direct route. Due to users' weak control to muscles and joints, the variation of the constraint force should be soft and gentle. The degree of constraint force can be adjusted according to the actual physical conditions of users during training process, to achieve different training difficulty.

Taking the control algorithm of straight trajectory in the active-constrained mode as an example: AB is the desired straight trajectory, $A(x_1, y_1)$ is the starting point and $B(x_2, y_2)$ is the end point. The normal force of AB at the end point of the exoskeleton restrains the end point on the desired trajectory; and the tangential force provides auxiliary power or resistance from A to B, to achieve weight loss or gain.

The coordinate system is shown in Figure 5 $A(x_1, y_1) = (0,0)$. The auxiliary line l_L, l_A, l_B divide the motion space into five sub-regions Ⅰ, Ⅱ, Ⅲ, Ⅳ, Ⅴ, of which l_A, l_B are lines passing through points A, B respectively and perpendicular to the line AB, l_L is line segment whose distance is DP to line AB, and DP is the prescribed maximum error beyond the trajectory line AB. $P(x_t, y_t)$ is the actual location of the end point of the exoskeleton. DPA , DPB , DPL are the distances from point P to lines l_L , l_A , l_B respectively, by which the sub-region where P is can be recognized. When P enters the sub-regionIII, and still close to the point A ($|D_{PA}| \le D_P$), the force output satisfies the following relationship: $F_{t+\Delta t} = F_{aim} \times |D_{PA}| / D_{PL}$, $\theta_{t+\Delta t} = \pi + \arctan((y_t - y_1)/(x_t - {}_1))$, and the direction is from $P(x_t, y_t)$ to A. When P enters the sub-regionIII, but far from the point A ($|D_{PA}| > D_P$),the force output satisfies the following relationship: $F_{t+\Delta t} = F_{aim}$, and the direction is from $P(x_t, y_t)$ to A. When P enters the sub-regionIV, the principle is similar within sub-regionIII . When P enters the sub-region I ($D_{PL} \ge 0$, and $|D_{PL}| \ge D_P$), the force output satisfies the following relationship: $F_{t+\Delta t} = F_{aim}$, $\theta_{t+\Delta t} = a\tan 2(-x_2, y_2)$. When P enters the sub-region II ($D_{PL} \le 0$, and $|D_{PL}| \ge D_P$), the force output satisfies the following relationship: $F_{t+\Delta t} = F_{aim}$, $\theta_{t+\Delta t} = \pi + a\tan 2(-x_2, y_2)$ .When P enters the sub-region V , within the range of error band ($|D_{PL}| \le D_P$),the force output satisfies the following relationship: $F_{t+\Delta t} = F_{aim} \times |D_{PL}| / D_P$, $\theta_{t+\Delta t} = a\tan 2(-x_2, y_2)$

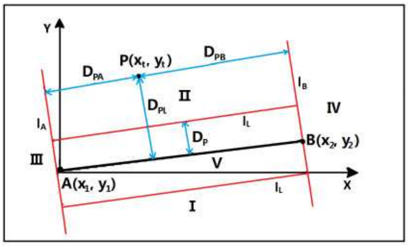

Figure 4: Control algorithm instruction

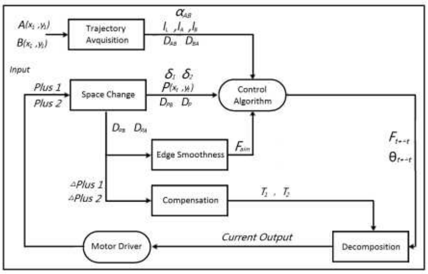

Figure 5: Active-constrained mode algorithm process structure

3 Experiment Results

To demonstrate the performance of the multi-posture locomotion training device, we have implemented three series of experiments: the repeatability and stability experiment of passive mode, and the accuracy experiment of active-constrained mode.

Ten healthy subjects are recruited to participate in these three series of experiments. All subjects have no history of serious diseases (6 men and 4 women, mean age: 24.5 years, range: 22-28). All subjects participate with informed consent and the approval of the local ethics committee. None of the subjects participate in similar experiments previously.

Figure 6: One subject's experimental process

3.1 The repeatability and stability experiment of passive mode.

The purpose of the experiment is to test the repeatability and stability of passive mode. In this experiment, step frequency is 0.2Hz, and the angular transducers fixed outside of the hip and knee joints of the exoskeleton collect angles changing with time as shown in Figure 7.

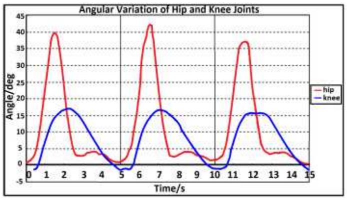

Figure 7: Angular variations of hip and knee joints

The motion parameters are accurate with a good reproducibility, because of the strong enough constraint force which is provided to lower lime by the exoskeleton in the passive mode. We calculate the maximum relative errors of hip and knee movement angles of the 10 subjects in the passive mode, and the results show that the relative error of the knee joint is slightly higher than the hip, but all are less than 6% as shown in Figure 8.

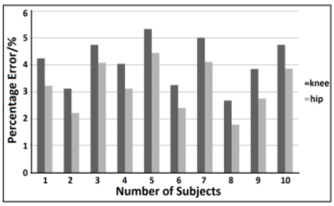

Figure 8: The results of the repeatability and stability experiment of passive mode.

3.2 The accuracy experiment of active-constrained mode.

Subjects do reciprocating linear motion without restraint, when the track is within the error range, the exoskeleton follows up; When the track is out of the error range, the exoskeleton provides constraint force to reconnected lower limb within the error range. The experiment is to prove the accuracy of the straight trajectory which subjects participate in under the active-constrained mode.

Angles of hip and knee joints are collected in the same way as passive mode to calculate positions of the end of the exoskeleton by kinematics positive solution, and then the trajectories composed of these positions are drawn out in the sagittal plane in Figure 9. The results show all the trajectories are within the error range (block representing the error range in the Figure 9).

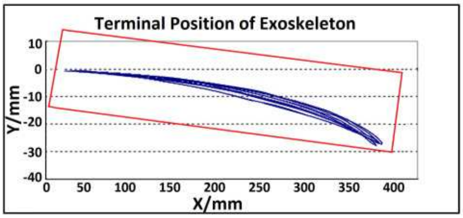

Figure 9: The results of the accuracy experiment of active-constrained mode.

4 Conclusions

This article provides the closed-loop control to accuracy control for the MPLTD. By introducing a force-field control, a new active-constrained mode is proposed for the indifferent equilibrium mechanism. The novel active-constrained mode is constructed by the matrix between trajectory and force field. A series of trajectory accuracy experiments in various angles demonstrate a satisfactory performance of the active-constrained mode. Considering the fatigue and aging of the indifferent equilibrium mechanism, we will focus on robust adaptive control for the MPLTD in the future work.

References

[FGO12] Fryar, D.; Gu, Q., Ogden, L.: Anthropometric Reference Data For Children And Adults: United States, 2007–2010. National Center for Health Statistics, Vital Health Stat, 2012; 1-40.

[RB13] Reese, B.; Bandy, D.: Joint Range Of Motion And Muscle Length Testing, Elsevier Health Sciences, 2013.

[Br72] Brunnstrom, S.: Movement Therapy in Hemiplegia: a Neurophysiologic Approach. J Gerontol, 1972; S.2904.

[CBN11] Candace, T.; Beth, P.; Nicholas, E.: Efficacy Of Rehabilitation Robotics For Walking Training In Neurological Disorders: A Review, J Rehabil Res Dev, 2011; 387-416.