Stroke Patients Walk Pattern Prediction and Tracking Control Method for a Novel Intelligent Lower Limb Rehabilitation Walker

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ABSTRACT

Aim to accelerate the process of lower limb rehabilitation for post-stroke people, various intelligent lower limb rehabilitation walkers (ILLRW) with body kinetic analysis and feedback control function have been developed to reduce the nursing workload and enhance training performance. In this work, a novel ILLRW is proposed, equipped with a walking remote system via control lever and driver units to assist user's walk correspondingly. However, the walking ability varied significantly from stroke persons, and a system that can interfere with the driving system to adjust the speed according to the pace is critical. Thus, we also developed a walk pattern prediction system (WPPS) to feedback and further optimize the control system. The WPPS includes a laser range finder (LRF) array and plantar pressure sensors at the bottom, wearable pressure sensors at the user's waist, and an Inertial Measurement Unit (IMU) at the user's body joints. Altogether, the data get further analyzed and a walk pattern model generated while walking, and it is expected that the movement of the walker can relatively match the user's pace. Experimental result shows that our WPPS can track stroke patient's movement pattern effectively.

KEYWORDS

stroke patients, walk pattern prediction, tracking control method, lower limb rehabilitation walker

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1 INTRODUCTION

Lower limb dysfunction, caused by stroke, reduces the quality of life significantly. People suffering moving limitations on leg and foot cannot support their own weight and need supporting equipment to rely on, and a proper rehabilitating walker can accelerate the recovery process on balance ability and muscle strength [1, 2]. In fact, there is a lack of efficient therapies for this issue in the hospital, and the passive frame walker does not have any drive control is what they used most often [3]. On the other hand, considering the stroke patients' lower limb kinetic pattern is complex [4]. Thus, dynamic adjustment to parameters of walker control by track patients' actions and gait is a key issue for intelligent lower limb rehabilitation walkers (ILLRW).

At present, to acquire body kinetic data for movement tracing control of walkers, some research uses foot pressure and 3D motion data to calculate the user's center of mass [5]. Gait data can also be acquired by using the depth image algorithm, and the user is guided by the calculated visual cues for rehabilitation walks [6]. Also, body kinetic data is used by various intelligent walkers, which are proposed to assist lower limb rehabilitation training. By computing the center of pressure of the user's hand and leg motion, a cane-shaped robot is proposed to detect the user's fall down and take fall prevention impedance control [7]. The user's intention or tendency for a movement is recognized by suppressing the armrest mounted on the walker while path tracking training is performing [8]. Marker trajectory and reacted force from the surface also applied to recognize a post-stroke patient's gait [9]. Still, lower leg motion analysis is of different role and functions towards ILLRW, i.e., to control the walker move forward or backward relatively correspond to patient's pace, and within this topic, deciphering fall down tendency, walking ability, and speed is important.

The paper proposes a novel ILLRW with a walk pattern prediction system (WPPS), and the patient's pace speed is recognized by our algorithm, to control ILLRW move accordingly. We consider the work would help fill the gap between stroke patient's movement and the tracking system of intelligent walkers.

2 STRUCTURE OF ILLRW

The ILLRW this work proposed is divided into two main systems, which are WPPS for motion pattern analysis and drive control system (DCS) for adjusting ILLRW moving speed corresponded to pace.

Figure 1: Structure and sensor installation of the ILLRW. Photograph by author.

Figure 1 shows the overall structure. To ensure safety, the strong frame, hand-holders which are also parts of the frame, and waist fix is equipped onto the ILLRW. The whole system is powered by a Li-Po battery which can provide the system pure and stable current. Multiple sensors are installed onto the system and controlled by two ATmega2560 MCUs, which are responsible for body kinetic data recording and transporting to an upper computer. Considering stroke patients' walk abilities varied greatly, pace machine-track-pace mode (conducted body motion data) and manual operating mode (conducted by linear control lever) are provided, and in this work, we focus on the former one which is a prevalent approach in relative research issues. Turing and machine walking torque are transferred from a step motor and DC motor.

To start training and analyze data from this system, firstly patient should fasten the waist holder belt for safety and fine communication with the pressure sensors, and hands hold the waist holder. Then attach the six 9-axis sensors (three on both sides) onto the user's legs. Finally, turn on the power and press the timer start button to start training with WPPS and DSC system.

3 INSTALLATION AND WORK PRINCIPLE

In this work, the WPPS and DCS work corresponding and simultaneously, the overall control logic diagram is shown in Figure 2

Safety during the walk should be considered first since the ILLRW walks autonomously, thus the WPPS contain three kinds of sensors

Figure 2: Overall control logic diagram.

and control algorithm to realize the machine track and fall down prevention. We aim to make it fully understand patient's intention, further predict next behavior, and recognize danger quickly, then take immediate actions.

3.1 LRF sensor array

The LRF sensors measure the range between lower fore-end of the walker and the patient's lower leg, this kind of sensor use triangulation method so that the object should be in straight front of the sensor. Thus, in this work, to measure the largest range of change and the most obvious leg movement characteristics, on their laser emitting directions, they should be as close as possible to patient's foot, while foot shouldn't be recorded and leg shouldn't be ignored provided leg moves irregularly. To achieve this, we use a sensor array to make sure there always be at least one sensor

Figure 3: The installation positions of the sensors, and the mechanism part. Photograph by author.

outputting the most effective data. In this setting, the LRF sensor array can sense the step length, and during the walk, the foot relative distance to time curve is known for further foot movement character analysis. Also, where there is a tendency to fall down, the sensors will capture an exceeding leg safe range limit and send commend to DCS.

3.2 Waist pressure sensor array

The waist pressure sensor array can provide precise waist pressure in four directions as shown in figure 2, and fastening the waist belt is important since this data is generated precisely by contacting force. Thus, the waist holder can be adjusted horizontally, and waist belt can be fastened. So far, patient's intention for directions and speed to move is known, and this data is converted into a linear controlling signal towards DCS for driving the ILLWS move correspondingly. And by sensing a dragging from directions, walkability can be assessed.

3.3 9-axils IMU array

The full pattern data of leg motion is generated by the IMU array, which is measuring hip, knee, ankle joints in angle, acceleration, and gyro data. And accordingly, they are installed (attached) onto these joints for they give the most obvious dynamic data. By calculating the joint acceleration, leg stretch can be estimated, and by analyzing the joint angle, leg movement patterns can be deciphered, i.e., part of patient's gait. Figure 3 shows the installation positions of the sensors and the mechanism part.

3.4 Drive control system

Control command is generated by above body movement data via ATmega2560 MCU and control the DCS move accordingly. The actuators include a linear PWM signal-controlled DC motor driving system that tracks patient's movement quickly and smoothly via PID algorithm, and a turning power chain mechanism and step motor.

Considering co-walk safety, walking speed and direction shouldn't be changed arbitrarily by transverse plane thrust of body

Figure 4: Mechanical design of the front wheel.

during training. Thus, the ILLRW reserving enough torque for holding patient while walking, and pushing or pulling patient to retrieve balance. Also, a worm gear reducer that transfer torque in one way is installed onto the turn power chain, and the front wheel can't be rotated despite controlled by the linear control lever. The motor type selection follows the below formula.

$$J = J_{FW} \frac{\omega_{FW}^2}{\omega_R^2 \eta_F} \quad (1)$$

where J is the total inertia for the system. As discussed previously, the turning torque is transferred through a worm gear reducer, the inertia should be reduced after this. The J_{FW} is the total inertia of the front wheel and system, ω_{FW} is angular velocity of the front wheel, ω_R is angular velocity of the reducer, η_F is efficiency coefficient of the reducer.

Under control of the MCU, the ILLRW not only walk according to the body motion but also provide necessary support and forbid redundant movement to ensure training safety. An electrical clutch is set on the turning power chain deciding the transmission of turning torque. The ILLRW therefore has active and passive walk-assist methods. Figure 4 shows the mechanical design of the front wheel.

3.5 Software control flow

Figure 5 demonstrates the software control logic of the above functions discussed. All sensors report measured data to the ATmega2560 MCU, and MCU converts analog voltage from LFR sensors and pressure sensors to real meters and grams via our algorithm. IMU sensor reports angle-related data to MCU via TTL transmission. And then the analyzed data is transferred to a PC terminal for further understanding of gait and to the DCS for tracking control. An ATmega328 MCU is the controller of the DCS. A max and min speed of the walker is set as a constant, which are 1m/s max and 0.2m/s min, and if the speed exceeds the value, a loss of control will be recognized, then a brake activated reducing speed. Same as above, a speed lower than 0.2m/s is recognized as a sliding, and then the walker holds brake until next command has applied.

Figure 5: Software control flow chart.

Figure 6: Stroke patient's typical pace pattern and its angle measurement.

Within the value range, the ILLRW tracks body motion as precious discussed.

4 PACE PATTERN DEFINITION FOR STROKE PATIENT

A full understanding of the typical walk pattern for stroke patients is necessary for experiment design, and of what body position we should put the sensors on is critical for present walk locating and speed measuring. And to limit the variables, the patient's walk rhythm is corresponded by a metronome. Also, by precisely locate the sensors onto joints, prediction of next step can be realized via accelerated data. Figure 6 shows the Stroke patient's typical pace pattern and its angle measuring method, and the move limited leg is the measuring target.

Define the "green leg" as the move limited leg. While a patient is standing still, the legs are touching ground at the same time, and when he steps forward the healthy leg, the "green leg" keeps touching ground but move for some relative degrees. Then resume standing still since stroke people typically can't walk continuously and the pacing pattern is more like a healthy leg dragging a move limited leg, and so far one pace is finished for stroke people.

In this work, the focus is on how to measure the body overall movement by leg angles and feet range, and this data is demonstrated by analyzing in x, z plane. Thus, the pace pattern can be simplified as levers connected to joints regardless of foot and upper body movements. Now the angles from limb and vertical direction can be calculated which are θ_1, θ_2 , and the length of limbs is known as D_1, D_2 . Then the overall movement of body can be calculated by below formula,

$$D_{s0} = D_1 \sin \theta_1 + D_2 \sin (\theta_1 + \theta_2) \quad (2)$$

Figure 7: Tracking experiment. Photograph by author.

Note that the θ_1, θ_2 are two measured variables output from the IMU sensors, and the time stamp in millisecond is acquired by the inner clock of the MCU. With the angle value in real time, we can get the moving speed of body,

$$\Delta V = \frac{dD}{dt} \quad (3)$$

The distance data from LRF sensors is a reference value to the previously measured overall movement of body. Three sensors are available on one side as discussed previously, and one of them is a spare sensor for expanding scan range, and the other two are the main outputting sensors. The range variables from sensors to two legs are L_1, L_2, L_3 is more stable according to experiments we have done, thus we use the combination of the two values but of different weight, i.e., $\eta_1, \eta_2, \mu_1, \mu_2$, to improve the result accuracy. The final reference range is,

$$L_{left} = \eta_1 L_1 + \eta_1 L_2 \quad (4)$$

$$L_{right} = \eta_2 L_3 + \eta_2 L_4 \quad (5)$$

Also, IMU sensors output acceleration data, and the curve will be demonstrated below.

5 EXPERIMENT AND RESULT

5.1 Preparation

The ILLRW tracking performance is expected to evaluate in this experiment, and the ILLRW tracks the user closely will be the desired outcome. While the experiment is in progress, body motion data will be recorded through the sensors and demonstrated on a PC terminal for analysis, and become the command signal towards the DCS. And the data and curve chart from the pressure on waist is an evaluation criterion of tracking.

The experimental subject is a young male of 187cm, 95kg. while the experiment starts, the waist holder will tightly hug the waist, and IMU sensors will firmly attach to the joints as previously discussed. The subject walks about 15 steps according to a metronome of 40 BPM, and the walk method is according to Figure 6. The data is recorded during experiments. Figure 7 is the experiment pictures.

Figure 8: Angle data of left leg joints and range from frame-fixed sensors to ankles.

5.2 Results

In this experiment, the subject walk for 15 steps under the instruction of a metronome. Finally, we take the most stable and reliable curve on left leg in continuous 12 steps as shown in Figure 8. The curve refined by the Kalman algorithm, and demonstrate that the steps are in relative constant rhythm despite that the angles of joints vary slightly. And that means we can find a pace's start and endpoint easily by recognizing the peak and trough of the curve since leg reverses its rotating direction after a step, and this is critical for defining a start or end to all the other sensors, i.e., all the sensors' value should be synchronized by time to reveal exact outcomes. Also, the slightly varied angles indicate the varied pace length and speed. Then this data is calculated to the body move distance value corresponded to real-time, and to make the ILLRW move accordingly.

Also, the range from LRF array which fixed onto the front end of the frame to the subject's ankles is generated. As the Figure 8 is shown, the rhythm pattern of the curves is similar to the previous angle data, and this can therefore be a reference to the calculation of body overall movement. And if there is a tendency to fall down, the two curves will go up or down greatly and simultaneously.

Figure 9 shows the experiment data on joint acceleration. By applying the Kalman algorithm, the acceleration data from joints can be used to predict a next landing site. The velocity of leg is known as the previous discussion, and so far the acceleration data is acquired, then combining them with inertia of legs, thus the estimated landing site value is acquired.

Figure 10 compares two waist pressure patterns in WPPS aided mode and passive pushing mode. We take two tests to see the overall performance of the WPPS and DCS, one is walking with all functions on and one is walking with powered off. Since the only holder and pressure sensors are located on the waist, the pressure data can reflect how the system tracking user's movement. With help from the metronome, the walk rhythm is matched from different tests. And the peak pressure value of the tracking mode curve is far bigger than the other one. Thus the WPPS and DCS are proved effective.

Figure 9: Acceleration data of left leg joints.

Figure 10: Waist pressure in WPPS aided mode and passive mode.

6 CONCLUSION

In this work, we developed a novel ILLRW for post-stroke patients. Our primary concern is the safety issues, and the experiments show that the walker preliminarily possesses the active and passive safe insurance functions. Besides, another main objective of the walker is to help post-stroke patients recover and lower the nursing workload, and the experiments show it can track user's pace well. So far, we plan to get further researches on drive control systems combined with gait data.

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REFERENCES

- [1] Villa-Parra, A.C., Lima, J., Delisle-Rodriguez, D., Vargas-Valencia, L., Frizera-Neto, A., Bastos, T. 2020. Assessment of an Assistive Control Approach Applied in an Active Knee Orthosis Plus Walker for Post-Stroke Gait Rehabilitation, vol. 20, no. 9, pp. 2452, May. 2020.
- [2] R. Tan, S. Wang, Y. Jiang, K. Ishida and M. G. Fujie. 2013. Path tracking control of an omni-directional walker considering pressures from a user, 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Osaka, Japan, 2013, pp. 910-913. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6609649&isnumber=6609410>
- [3] Ying T. 2019. Application of Rehabilitation Training to Lower Limb Motor Function in Hemiplegia Patients. *China Reflexology*. vol. 28(no. 12):2.
- [4] Aoyama H, Hori H, Yonenobu K, Uegami K, Ogawa K, Jeong S. 2019. The movement of trunk and pelvis in the rolling stand-up walker: Primary research for the exploitation of rehabilitation walker. 2019 19th International Conference on Control, Automation and Systems (ICCAS); 15-18 Oct. 2019.
- [5] H. Aoyama, H. Hori, K. Yonenobu, K. Uegami, K. Ogawa and S. Jeong. 2019. The movement of trunk and pelvis in the rolling stand-up walker: Primary research for the exploitation of rehabilitation walker. 2019 19th International Conference on Control, Automation and Systems (ICCAS), Jeju, Korea (South), pp. 393-396. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8971570&isnumber=8971449>
- [6] C. D. Lim, C. Wang, C. Cheng, Y. Chao, S. Tseng and L. Fu. 2016. Sensory Cues Guided Rehabilitation Robotic Walker Realized by Depth Image-Based Gait Analysis, in *IEEE Transactions on Automation Science and Engineering*, vol. 13, no. 1, pp. 171-180, Jan. 2016.
- [7] <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7332986&isnumber=7370740>
- [8] P. Di *et al.* 2016. Fall Detection and Prevention Control Using Walking-Aid Cane Robot, in *IEEE/ASME Transactions on Mechatronics*, vol. 21, no. 2, pp. 625-637, April 2016. <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7258377&isnumber=7422867>
- [9] C. Cui *et al.*, 2018 Simultaneous Recognition and Assessment of Post-Stroke Hemiparetic Gait by Fusing Kinematic, Kinetic, and Electrophysiological Data, in *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 26, no. 4, pp. 856-864, April 2018, doi: 10.1109/TNSRE.2018.2811415.