Development of walking assist system for the people with lower limb-disability

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Abstract: There is some equipment that helps user to exercise and to walk. But almost all equipments require some physical strength of their muscles. So we developed a system that could assist walking action of the people with lower-limb disability. The system called as walking stand adopted the balancing mechanism which assures the stable walking, and the 4 link-based mechanism that had 2 degrees of freedom on each leg. The walking stand uses four motors and has two sets of the special link-structure to simulate the human walking mechanism. With our system, even serious disabled with lower-limb disability may enjoy walking rehabilitation. And by adjusting the power, it can be used as the walking assistant mechanism instead of conventional wheelchairs. Experiments showed that our walking stand is applicable to the rehabilitation and also to the mobile device in our daily life for those people who do not have enough physical ability to walk by themselves.
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Keywords: Parapodium, walking assist system, rehabilitation, lower-limb disability.

1. Introduction

Nowadays, due to the advanced medical technology and life environment, the percentage of the aged people showed tendency to increase, and the various accidents including car-accident produced many kinds of the disabled people. Recently, many medical centers, rehabilitative institutes and welfare institutions were built, and many tools were developed for the people with disability. And their life became easier and more convenient compared to a few decades ago.

And we are needed to think that those are really designed for user and really help user goes for the better life. For example, wheelchair has been the conventional moving vehicle for the lower-limb disability. But there are still so many problems to solve, even though the stairway has some equipment for the wheelchair, a steep slope allows only some users who have enough power. And the worst thing is that sometimes, despite people with disability may recover their walking-ability by doing rehabilitation, they still recommended to use the wheelchair because of the safety, and become not to try to walk. The best thing for the people with disability is not just helping them feel free on the wheelchair, the most valuable thing is helping them to walk again.

In this paper, we developed a system for the people with lower-limb disability to assist their walking and rehabilitation with enjoy. The proposed system may encourage people to walk again and may prevent various symptoms related with their bedridden status.

Many researchers have studied about walking assist. Parapodium was developed as walking stand without using any electronic system in Poland[1], Koyama researched wearable human assisting robot[2]. To help people with walking, Tsukuba Univ. developed HAL to assist power of the leg[3], Moromugi developed power assist system using pneumatic device[4]. And Honda is famous for ASIMO's walking mechanism using ZMP[5].

2 Concept of Proposed Walking Assist

2.1 Walking Stand

Fig 2.1 shows Parapodium that is developed for the people of limb disability in Poland. Parapodium fixes legs and waist of the user and has two long bars on each foot to make user not to fall. For walking, user has to swings his body and moves his weight on one side, and pushes the handle of the other side to walk forward. Parapodium has simple kinematical structure and does not use any electrical parts. In the aspect of the control, walking with it is not difficult even for novice. But because Parapodium does not assist user with power, if user does not have enough power on the muscle of the upper body, he cannot walk with it.

If this kind of the walking stand adopts the power assist system, it could help disabled user to reduce burden and to enjoy walking.

Fig 2.1 Parapodium

2.2 Walking Stand With Power Assist

The purpose of this research is the development of the walking assist system for the people with disability. Our target is to develop the power assist system that consists of four geared-servo motors, sensors, controller, and two sets of four-link based structure.

Human walking can be divided into two methods, static and dynamic. Under the static walking, human puts his weight point on the supporting leg and then starts to move other leg. Under the dynamic walking, human moves his weight point toward the supporting leg, and before his weight point is put on the supporting leg, he starts to move other leg.
Despite it is very efficient to use bust's reaction to keep balance, when he stops his motion during walking, it is also very hard not to fall. And for the maintenance, wearability and appearance, the system must be simple, light and safe.

From these considerations, we propose the targets of the power assist system as following :

① When user wants to stop, the system must stop at once.
② Always the system must keep stable balance.
③ The system must be simple, light and safe

We choose the static walking method and adopted Parapodium's balancing mechanism as the walking mechanism of our power assist system.

3. Base model

3.1 Mechanism of Base model

In order to verify the idea of our walking stand a base model is built as shown in Fig.3.1. In the base model, only one DC-motor is used to drive both legs alternatively. The power of the DC-motor is transmitted to both legs through pulley and wire. If one leg is moved forward, the other leg is moved backward automatically by the wire and the pulley. Basic mechanical structure is almost same to that of Parapodium and the system can keep balance at any time. Sensors are used to check walking status between ground and the system. Fig 3.1 shows the Base Model of the power assisted walking system.

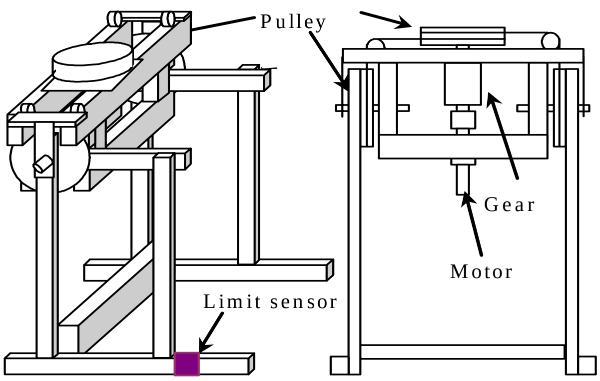


Fig 3.1 Base mode

With this base model, we verified the concept of the power assisted walking system, and became to know that the disabled people could enjoy walking and rehabilitation.

3.2 Control

Fig 3.2 shows the diagram of the control flow of the base model. As the main processor of the control, we used PIC16F873 that is cheap, compact and high-performance one chip processor. And FPGA was used to interface with sensors. PC was used to setup parameters of walking speed and stride. Sensor was set to the bottom of the foot to check the status of the body motion and PIC16F873 takes sensor signal from FPGA. According to the sensor's signal, controller perceives its walking status and sends next command to motor.

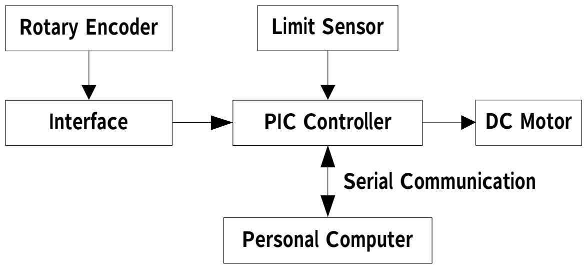


Fig 3.2 Diagram of Control Flow

3.3 Walking kinematics

Fig 3.3 shows walking pattern of the base model

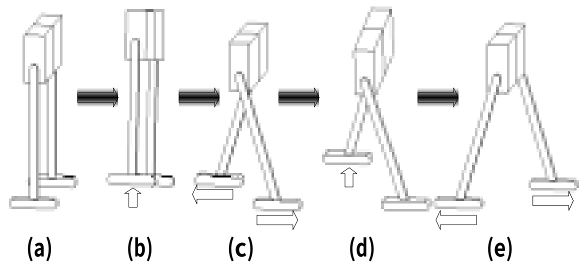


Fig 3.3 Walking pattern of base model

In the Fig 3.3, (a) shows initial position. Even user cannot keep balance, base model supports user to stand alone. When user declines his body to left, right leg is lift up (b), and the motor shifts right leg to forward and left leg to backward simultaneously (c). And then, if user declines body to right, his left leg is lift up(d), and the motor shifts right leg to backward and left leg to forward(e). By repeating these processes of the system, user can walk with it.

To verify the validity and safety of the base model, we did the experiment. Because the base model was not applicable to the people with disability, a healthy man was chosen to operate. Even though the base model had simple four-link structure and was powered by only one motor, the experiment showed that the base model could actualize the features of human walking mechanism, and user could be assisted. The experiment was executed in flat place without any obstacles.

4. Advanced Model

4.1 Four Link-Based Modeling

Through the experiment with the base model, we verified the power assisted walking mechanism and started to develop the advanced model that could actualize more complex motion of the human walking mechanism and more comfortable for user. Fig 4.1 shows main kinetic structure of the advanced model. The basic concept of the kinematics is same to the base model, but the additional links produces two degrees of freedom on each leg. So we used four motors for the advanced model to actualize the human walking.

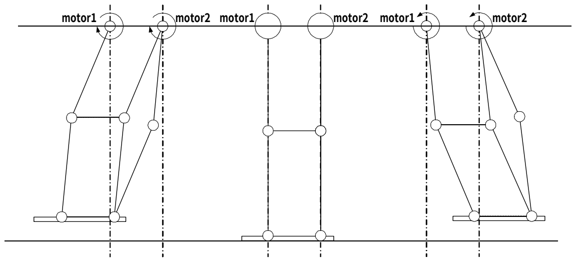
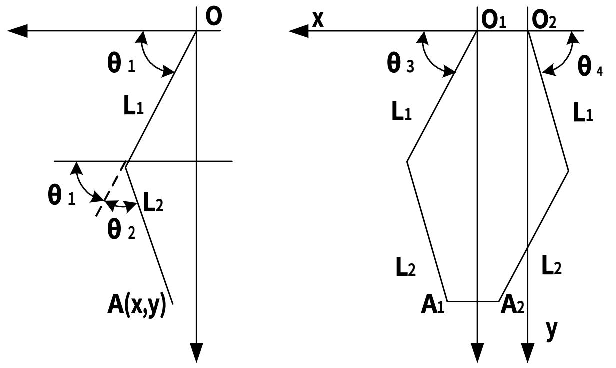


Fig 4.1 kinetic structure of advanced model

Motor1 defines the motion of upper leg (thigh) and motor2 defines the motion of lower leg (shank).

Geometrical relation of the mechanism can be derived as follows. Fig 4.2 shows the simplified link structure of the advanced model.



(a) (b)

Fig 4.2 Simplified link structure of the advance model

To find the position of A(x,y) from Fig 4.2(a), we obtain

$$x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) \quad (1)$$

$$y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) \quad (2)$$

and、

$$L_2^2 = \{L_2 \sin(\theta_1 + \theta_2)\}^2 + \{L_2 \cos(\theta_1 + \theta_2)\}^2 \quad (3)$$

From (1),(2), and (3)

$$y \sin\theta_1 + x\cos\theta_1 = \frac{\left(x^2 + y^2 + L_1^2 - L_2^2\right)}{2L_1} \quad (4)$$

where

$$a\sin\theta_1 + b\cos\theta_1 = \sqrt{a^2 + b^2}\sin(\theta_1 + \alpha) \quad (5)$$

$$\sqrt{x^2 + y^2}\sin(\theta_1 + \alpha) = \frac{x^2 + y^2 + L_1^2 - L_2^2}{2L_1} \quad (6)$$

$$\sin(\theta_1 + \alpha) = \frac{x^2 + y^2 + L_1^2 - L_2^2}{2L_1\sqrt{x^2 + y^2}} \quad (7)$$

$$\theta_1 + \alpha = \sin^{-1}\left(\frac{x^2 + y^2 + L_1^2 - L_2^2}{2L_1\sqrt{x^2 + y^2}}\right) \quad (8)$$

$$\theta_1 = \sin^{-1}\left(\frac{x^2 + y^2 + L_1^2 - L_2^2}{2L_1\sqrt{x^2 + y^2}}\right) - \alpha \quad (9)$$

$$\sin\alpha = \frac{b}{\sqrt{a^2 + b^2}}, \cos\alpha = \frac{a}{\sqrt{a^2 + b^2}} \quad (10)$$

$$\alpha = \sin^{-1}\left(\frac{y}{\sqrt{x^2 + y^2}}\right) \quad (11)$$

$$\theta_1 = \sin^{-1}\left(\frac{x^2 + y^2 + L_1^2 - L_2^2}{2L_1\sqrt{x^2 + y^2}}\right) - \sin^{-1}\left(\frac{y}{\sqrt{x^2 + y^2}}\right) \quad (12)$$

We can calculate the angle of θ_1 from (12) in Fig 4.2(a). The advanced model has the closed link structure as shown in Fig 4.2(b). And if L1 is equal to L2, and $\overline{O1O2}$ is equal to $\overline{A1A2}$, it becomes simple to find θ_3、 θ_4 in Fig 4.2(b).

4.2 Prototype of Advanced Model

Fig 4.3 shows the detail of the advanced model that actualizes human walking mechanism with four-link based structure. It is designed to keep balance and not to fall during walking for the safety of user. All motors are placed near the waist of user and one leg can supports about 60kg within some angle of θ_3、 θ_4. In this link structure, load is divided to two motors and we can choose smaller motors.

Because the system has only 2 degrees of freedom on each leg, same Parallel link structure is applied to the shank assembly and foot, so the foot always keep same angle to the absolute coordinate of the system. On foot, there is a large curve on its bottom to help user to swing his body easily and a long bar to support user not to fall. And two limit sensors are set to foot and upper leg to get the state of the walking motion .

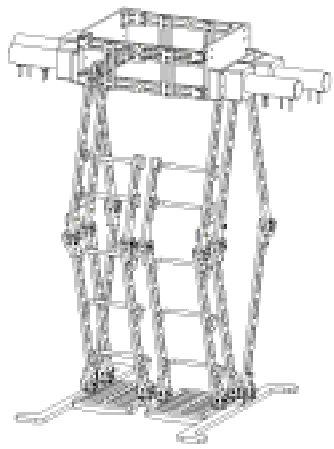


Fig 4.3 Mechanism of advanced model

Fig 4.4 shows the walking pattern of the advanced model. Basic walking pattern is almost same to the base mode, but the advanced model can fold legs.

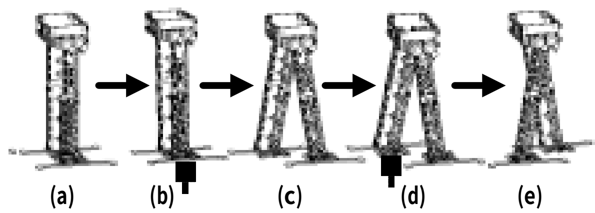


Fig 4.4 Walking pattern of advanced model

4.3 Control of Advanced Model

[Interface]

There are two sensors on each leg, one is set to the declined part of the bottom of foot to check body's inclination and the other is set to upper leg to check the intention of user not to move unproperly.

[Control Scheme]

In this research, we used PIC as the main processor of the advanced model. Fig 4.5 shows a control scheme.
The controller that includes PIC puts out pulse to motor-driver that moves motors. Through the driver, the data of rotary encoder of the motor is transmitted to the controller.

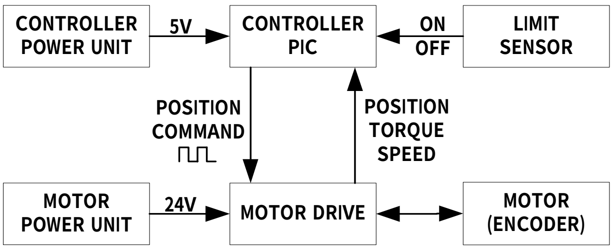
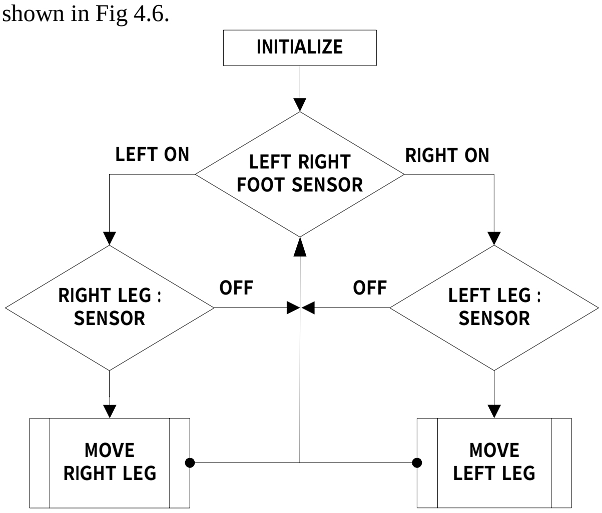


Fig4.5 Control scheme of advanced model

As shown in Fig 4.5, PIC uses 5V and motor driver uses 24V as control power. To minimize the noise control board is made of one board and shield cable is used between motor drivers and motors. In motor driver, we used position control method to control motors. And two PICs are used in each leg. One is for calculating the orbit of the foot, and the other is for calculating number of pulses and putting out them to motor-driver. Between PICs, communication is executed by I2C protocol.

[**Control command flow]**

The system performed the walking though the process shown in Fig 4.6.



4.6 Flow chart of PIC Controller

To prevent mal-function and to keep safe walking, the controller can't move leg unless both sensors are switched ON at the same time. To move left leg, left leg sensor and right foot sensor must be switched ON, and to move right leg, right leg sensor and left foot sensor must be switched ON.

5. Experiment

We tested the validity of the advanced model through experiments. The weight of the system was about 18kg, and dimension is 600x900x1023mm in its initial posture. The size of the advanced model was designed for a man, who is 165cm height and 55kg. And the experiment had been executed at the place that had no obstacle. A man with no disability tested the walking stand . And we had computer simulations to try out various orbit of the motion.

To verity the advanced model, we performed the experiment in the point of the standing stability, walking stability, and walking mechanism. Firstly, we did the experiment without a supporting bar settled at the bottom of the foot as shown in Fig 5.1. Despite the bottom of both foot had slant of large arc, at the standing posture, user could rest and move his body on the system. When he swung his body, the system swung according to user will. But as he swung a little more, he became to feel unstable, the adjustable swing-limiter of the foot did not cover large swing angle. Also during walking, user felt anxiety about falling to side. So we revised the swing-limiter to long and wide as shown in Fig 4.4. By revising the swing-limiter, user felt stable at the standing posture and during walking. And because the range of the body motion became wide, user became to move bust to a distance.

At the walking experiment, we operated the system step by step to check each motion progress. With the initial position, user started to swing his body and moved one leg when the leg sensor and the other foot sensor became ON. What user had to do was just swinging his body and keeping body balance, and putting little weight to turn on the leg sensor.

(a) front (b) side

Fig5.1 wearing the advance model

In consequence, we could verify the validity of the advanced model as a walking stand with power assist, but found some issues that must be improved. They are total weight of the system, the size of the swing-limiter and backlashes of the geared motors.

Because the weight of the system and user limit rotating range of the links, it is required to reduce the weight of the system but do not reduce the robustness of the system. And the size of the swing-limiter must be considered in two points, stability and space, the large one enlarges stability of the system, but needs more space to walk.

The length of the link of the advanced model was 450mm and backlash of the geared motor showed a little large deflection at the end of the system so called foot's orbit. Despite our system does not require high accuracy, if backlash can be reduced, the performance of the system will be improved.

6. Conclusion

As mentioned in the introduction, many research and basic study of human welfare are taken place in many countries of the world. Our research focused on the people of lower-limb disability and developed a power assistant system for people with lower limb-disability. And verified it by the computer simulation and the experiment. Main components of the system are two sets of four-link mechanism wearable by the user. The mechanism realizes walking action of the user. The experiment is carried out with various foot's orbits by adjusting parameters. The result shows that our power assist system is applicable to the rehabilitation and also to the mobile device in our daily life for those people who do not have enough physical ability to walk by themselves.

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