Development of a Novel Pneumatic Power Assisted Lower Limb for Outdoor Walking by the Use of a Portable Pneumatic Power Source

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Abstract—In our previous research, a novel portable pneumatic power source, called a Dry Ice Power Cell, was proposed. In this paper, a novel pneumatic power assisted lower limb is developed by the use of the power of Dry Ice Power Cell. For those people whose muscle and balance remains in good condition but who have joint pain (hip or knee joint) in their leg and are unable to walk outdoors for long, the developed device can partially lift the patient in a comfortable way by pneumatic cylinder when the affected leg touches the floor, reducing the loads to which it is subject as well as the pain joint forces, thus relieving pain during walking. The developed device has the characteristics of a simple structure, low weight, easy to put on and take off and with sufficient capability to bear about 40% of the body weight during about 1000 steps of outdoor walking, using the power of Dry Ice Power Cell. The developed device can assist with outdoor walking not only over flat ground but also sloped and stair areas. In this paper, the structure and function and experiments involving the developed pneumatic power assisted lower limb are described in detail.

Index Terms—Walking Assist, Pneumatic Power Source, Joint Pain, Wearable Fluid Power

I. INTRODUCTION

Since our society is rapidly aging, old people with walking difficulties are expected to increase rapidly. Therefore, there are increasing needs of walking assistance device for the old people. Although well known aids such as canes, crutches and walkers have been widely used, they require the use of user’s hands which limit the person’s ability to carry items and may cause fatigue and soreness of the hands. Wheel chairs have also been widely used, but the wheel chair’s total obviati of the need to use one’s legs prevents old people from gaining valuable exercise, thus can lead to further reducing ability to use their limbs. In order to develop a comfort walking assist device with advanced function and liberate the hands, powered assist device is believed an effective way. However, because all components of such device including actuator, power unit and control system are required to be carried by a person, it is necessary for all the devices made in light weight and compact size.

Many efforts have been put on developing powered walking assist devices in the past [1]-[4]. Many of them used pneumatic power actuator, because it has the characteristics of simple structure, high force to weight ratio, human friendly and safe which make it easier to realize a practical application. However, a common problem on these devices is power. No suitable portable pneumatic power source exists and only traditional installed air compressor was used which is too big and heavy. Such a heavy air compressor will drastically impair the compactness of pneumatic system. It is believed that to realize a practical powered outdoor walking assist device, a portable pneumatic power source is necessary.

In our previous research, a novel portable pneumatic power source, called a Dry Ice Power Cell, was proposed [5]. In this study, a novel dry ice powered pneumatic power assisted lower limb, called a DPAL, is proposed by using Dry Ice Power Cell as its power source. Since DPAL is supposed always carried by people while walking, the portable pneumatic power source, Dry Ice Power Cell is needed. DPAL is designed to be used for those people whose muscle and balance remains in good condition but who have joint pain (hip or knee joint) in their leg and are unable to walk outdoors for long. DPAL provides a saddle supplied with a hip fastening device. A pneumatic cylinder and a telescopic pipe beneath the saddle can partially lift the patient in a comfortable way when the affected leg touches the floor, reducing the loads to which it is subject as well as the pain joint forces, thus relieving pain during walking. DPAL has

NOMENCLATURE

A : cross area of cylinder piston
f : load threshold
f_s : assist force
f_ref : reference assist force
f_a : affected leg load
f_h : healthy leg load
f_L : total affected leg side load = f_s + f_h
\( g \) : acceleration of gravity
K : assist ratio
m : body weight
P_ref : reference cylinder pressure

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C. Control algorithm

The relationship between leg force and assist force from DPAL is illustrated in Fig.4.

When the affected leg is in stance phase, the affected leg load $f_b$ is measured by the insole force sensor inside the affected leg shoe. When the measured data is larger than load threshold $c$ ($c = 20kgf$ in this study), air cylinder starts to extend to provide assist force. When the reference assist force $f_{a\text{ref}}$ to load increment $(f_b - c)$ ratio is defined as assist ratio, the following equation can be given.

$$f_{a\text{ref}} = \begin{cases} K(f_b - c) & (f_b > c) \\ 0 & (f_b \leq c) \end{cases}$$

(1)

Assuming the retract spring of air cylinder is weak, and slide friction between piston and cylinder can be neglected, the reference pressure of air cylinder can be calculated by equation (2).

$$p_{\text{ref}} = \frac{f_{a\text{ref}}}{A}$$

(2)

Moreover, total affected leg side load $f_L$ can be calculated by equation (3).

$$f_L = f_b + f_a$$

(3)

In addition, assuming that walking speed is slow, and the influence from inertia force of bodyweight can be neglected, the relationship between healthy leg side load $\tilde{f}_b$ and $f_L$ can be given in equation (4).

$$f_L = mg - \tilde{f}_b$$

(4)

Such load threshold setting is because when the maximum affected leg load is reduced to a tolerable level, joint pain will be released. As shown in Fig.4, affected leg load is reduced from A-A' to B-B' level, the load incline is also decreased from CA to CB. Only by adjusting two parameters of $c$ and $K$, even to random human motion, a continuance walking assist control can be achieved. That is another merit for such settings.

III. DESCRIPTION OF THE STRUCTURE

Photo and construction of the developed DPAL is illustrated in Fig.5. It comprises a saddle, an air cylinder, a telescopic pipe with innerpipe lock mechanism inside, a rubber foot, furniture, and a electro pneumatic transducing regulator.

As illustrated in Fig.6, DPAL has characteristics of simple in structure, lightweight. The weight of DPAL is merely 2.5kg, Dry Ice Power Cell is 1kg, and total weight is 3.5kg. In addition, since DPAL is made up of universal parts, it is possible for further lightweight.
As illustrated in Fig.7 and Fig.8, an insole force sensor which can be easily put into shoe is developed. The upper surface of insole force sensor is a tough soft plastic plate cover. Four film type pressure sensors, called FlexiForce sensors (Tekscan co.) are inserted between four pairs of hard plastic plate, and adhere to the soft plastic plate. The under surface is covered with a soft cloth. The insole force sensor system uses a 9 volt battery for 6 hours measuring.

B. Innerpipe lock mechanism

The stageless adjustable telescopic pipe with innerpipe lock mechanism inside is a remake of a “Free lock stick” (SUMITA co.). In order to explain the principle of it, the sketch graph is illustrated in Fig.9.

When the affected leg foot steps on the furniture, pipe C is lowered, the spring beneath it is compressed and C is separated from link B. The B will open wider by the force of a torsion spring thereon and its three shafts closely contact with a square rod A. B has a top end connecting with pipe2 through a pin, while the top end of A is fixed on pipe1. When A is pushed downwards, B will open wider and its three shafts strongly press against A to form a secured lock, thus pipe1 and pipe2 are locked together. On the other hand, when the affected leg is in swing phase, the compressed spring raises C, C push B to make it close narrower, three shafts of B separate from A without pressing it, thus A will pass B freely and pipe 1 and pipe2 are unlocked. By this way, B can lock the telescopic pipe at any position whenever the foot touches the ground and unlock it whenever the foot starts to swing. The telescopic pipe can change its length within 150mm, and can bear more than 100kg bodyweight. By this design, not only the swing movement is not restricted but also the gas consumption is decreased because the necessary stroke of the air cylinder is reduced to the minimum.

A BF cylinder (FUJIKURA co.) is chosen as air cylinder. Because the BF cylinder chamber is total sealed by a rubber diaphragm and no contact friction occurs between the piston and cylinder. Moreover, a copper sliding bearing guides the piston rod, so there is no gas leak and little resistance in the air cylinder. An electro pneumatic transducing regulator (SMC ITV2051-212s) is chosen for controlling the air cylinder pressure for its small in size and electricity saving (electricity consumption is less than 3 watt).

IV. EXPERIMENT

A. Output of Insole force sensor

The experimental setup for confirming the accuracy of insole force sensor is illustrated in Fig.10. The measured force from the insole force sensor and a load cell is recorded into a computer simultaneously.

As illustrated in Fig.11, the experimental results of the insole force sensor and the load cell shows that two results are quite consistent. However, it is found that the insole force sensor is sensitive to some extent to the ground touch pattern which causes some inaccuracy.

B. Experiment on testing stand

The experimental setup for confirming the function of DPAL is illustrated in Fig.12. In order to examining the relationship between the foot load and the assist force, developed insole force sensor is not used, and a testing stand with three load cell is used to measure the foot force and assist force instead. An 80kg weight person stands on two load cells while DPAL is located on the third load cell. Torso weight is alternately transferred between the left and right legs while DPAL provides assist force simultaneously. The
measured data is recorded into the computer. In addition, measured signal by load cell under the affected leg is transferred to the controller. Then the controller generates control signal, and sends it to electro pneumatic transducing regulator, thus controls the pressure of air cylinder according to the reference pressure calculated on equation (2).

![Fig.12 Experiment setup for testing the response of the DPAL](image)

Control parameter setting is load threshold $C = 20\text{kgf}$ and assist ratio $K = 1$. A sample of experimental results is illustrated in Fig.13 which show the maximum affected leg load is reduced about 30kg. The experimental results confirm the effectiveness of the DPAL. In addition, the experiment confirms that DPAL can assist walking for about 1600 times (about 1hour walking assistance).

C. Experiment on flat ground

The walking assist experiment using the insole force sensor is also done. The experimental results sensed by insole force sensor are shown in Fig.14. The effectiveness of DPAL is confirmed. However, as illustrated in the circle mark in record2 of Fig.14, because the inaccuracy of the insole force sensor, the maximum total leg load $f_a + f_b$ is sometimes larger than the bodyweight 80kg, which shows there are mistakes in measuring leg force.

![Fig.13 Experimental result sensed by load cell ($K = 1$)](image)

D. Experiment on slope and stair areas

As illustrated in Fig.15, the experiment of using DPAL on slope and stair areas is also done. Notice that the DPAL does not actually output assist force in this experiment because the unfinished of embedded controller and only the function of innerpipe lock mechanism inside telescopic pipe is confirmed. In addition, DPAL is confirmed to be able to overcome any obstacle lower than 150mm.

![Fig.14 Experimental results sensed by insole force sensor ($K = 1$)](image)

V. DISCUSSION

In order to confirm the stability of the DPAL, the assist ratio $K$ is raised from 1 to 2, the walking assist experiment when maximum assist force is raised to 40kgf is done. From the experimental results shown in Fig.16, DPAL appears to resonate with torso and oscillation occurs, and makes the walking assist force unsteady. When the assist ratio is raised further, the situation becomes worse and worse. This is because when the assist force from DPAL is large, that also means a large disturbance on the measurement of the affected leg force.

![Fig.16 Experimental result sensed by load cell ($K = 2$)](image)
In order to improve the stability of DPAL, the insole force sensor is moved from affected leg side shoe to healthy leg side shoe, and the healthy leg load $\bar{f}_b$ is used for generating the control signal instead. From equation (3) and (4), the following equation can be given.

$$f_b = mg - f_a - \bar{f}_b$$  \hspace{1cm} (5)

Moreover, $f_a$ in equation (5) is replaced with $f_{a\text{ref}}$ and substitute it to equation (1), the following equation can be given.

$$f_{a\text{ref}} = \begin{cases} \frac{K}{K+1}(mg - c - \bar{f}_b) & (\bar{f}_b < mg - c) \\ 0 & (\bar{f}_b \geq mg - c) \end{cases}$$  \hspace{1cm} (6)

As shown in Fig.17, the walking assist experiment of DPAL based on new setting of insole force sensor and control algorithm is done.

![Fig.17 Control system with insole force sensor in healthy leg](image)

When assist ratio $K$ is 1 and the maximum assist force is 30kgf, experimental results are shown in Fig.18, which shows a stable walking assist is achieved. In addition, even when assist ratio $K$ is raised to 5 and maximum assist force is raised to 50kgf, as shown in Fig.19, a stable walking assist is achieved and no resonance with torso and oscillation occurs.

The reason of improvement of stability is because when the assist force is near the maximum force and resonance with torso is mostly easy to occur, the healthy leg is in swing phase and the assist force makes no disturbance with the insole force sensor at that time.

VI. CONCLUSIONS

In this study, a novel pneumatic power assisted lower limb, called a DPAL, is proposed by using Dry Ice Power Cell as its power source. The structure and control algorithm is also proposed. DPAL is confirmed useful for those people whose muscle and balance remains in good condition but who have joint pain (hip or knee joint) in their leg and are unable to walk outdoors for long. It has the characteristics of a simple structure, low weight, easy to put on and take off and with sufficient capability to bear about 40% of the body weight during about 1000 steps of outdoor walking assist. It can assist with outdoor walking not only over flat ground but also sloped and stair areas.

![Fig.18 Experimental result sensed by load cell ($K=1$) (controlled by measured value of $\bar{f}_b$)](image)

![Fig.19 Experimental result sensed by load cell ($K=5$) (controlled by measured value of $\bar{f}_b$)](image)

REFERENCES


