A Novel DGO Based on Pneumatic Exoskeleton Leg for Locomotor Training of Paraplegic Patients

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Abstract. This work introduces a new driven gait orthosis (DGO) based on the pneumatical exoskeleton leg for locomotor training. This device can drive the lower-limb of a patient in a physiological way on the moving treadmill following the given gait which fits to the individual needs. Therefore, it can help a patient who suffers lower-limbs paralysis to recover his walking ability. Mechanisms were designed based on the optimization from the view of human gait and the Ergonomics. Displacement sensors were mounted to allow a closed-loop control consequently to make each limb's motion as similar as possible to that of the human specimen. Each actuator is controlled by an algorithm, which consists of fuzzy and bang-bang. This solution allowed the existing strong nonlinearities to be easily managed with high response. The satisfying experiments results demonstrated the effect of the hybrid algorithm.

Keywords: gait, orthosis, pneumatic, exoskeleton, fuzzy, paraplegic.

1 Introduction

Recent studies have confirmed that locomotor movements can be induced and trained in paraplegic patients using partial unloading of the body while standing on a moving treadmill. Other results also proved that paraplegic patients who have taken such a locomotor training acquired greater mobility compared to the other control group without training. In order to improve the treadmill training for patients and reduce the workload of the therapists, a driven gait orthosis (DGO) has been employed in this study. This device makes it possible to apply automated locomotor training to nonambulatory patients even without the assist from other people.

Many researchers have proposed ideas to develop DGO in different ways. In 1972, Hughes developed a plan for a pneumatically driven exoskeleton[2]. Pneumatics is ever-adaptable and ever-innovative and has earned itself a major role in many fields. In addition, pneumatic cylinders are inexpensive and relatively lightweight for the amount of force they can deliver compared with servo motors. Kinematics control of a pneumatic system is an alternative solution for positioning applications, which can eliminate the complexity, expense and maintenance of motors, large power supplies and servo amplifiers associated with conventional motion control systems. Therefore, this research is focused to design a new DGO device based on the pneumatic driven exoskeleton legs which paraplegic patient can wear to take locomotor training.

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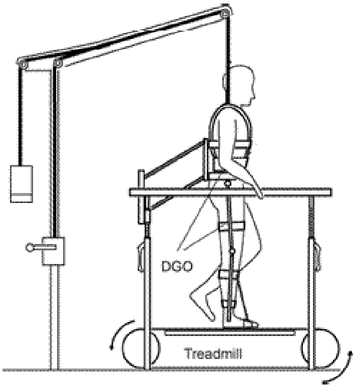

Fig. 1. Illustration of a Locomotor Training Device with DGO[1]

In the past, some research groups presented different ideas to develop a DGO using pneumatic devices.

The University of California has developed a pneumatically operated gait orthosis (POGO) controlled by a proportional position controller[3]. The Department of Mechanics Polytechnic of Turin also has developed a pneumatic active gait orthosis controlled by PLC for many years[4]. Recently, some Korea universities tried to develop a DGO using pneumatic muscles[5], [6] and also gained some results. In addition, the University of Minnesota presented a stored-energy gait orthosis, which could be driven through a complete gait cycle using only stimulation of the quadriceps muscles.

Although they can be used as DGO, they can't be called exoskeleton because they aren't designed according to the Ergonomics and only can be called assistant device for locomotor training.

2 Mechanical Design

In order to design a DGO based on exoskeleton leg that can fit the patient perfectly, the exoskeleton mechanical structure must accord with the Eagonomic's principles very well. In other words, the exoskeleton mechanical design will ensure that patients will not feel any counterwork when they wear this device.

2.1 Physiological Model and Mechanical Model

This exoskeleton leg must be the same joints in the right position and the same degree of freedoms in the right distribution to make itself analogous to the human lower-limbs. Human leg has three joints, hip, knee and ankle. There are related muscles driving separate joints.

Physiological model of the leg consists of muscles, bones and other many complex ingredients. Therefore, it is impossible to build a perfect mechanism to simulate such a complicated model. However, it is feasible to build a simplified model in mechanism to realize most functions that human lower limb has.

Human's hip joint equals to a spherical joint in mechanism. It has 3 rotation DOFs, the same as the ankle joint. Whereas, the knee joint equals to a revolute joint in mechanism. It has 1 rotation DOF and only rotates in the sagittal plane. Defined the joints and DOF, Fig.2 shows the human leg bone and primary mechanical model:

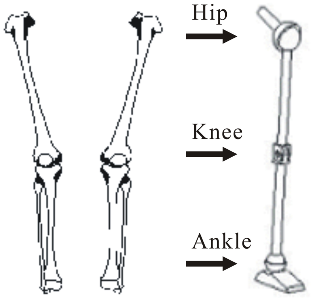

Fig. 2. Physiological model corresponding to Mechanical model

In Fig. 3, there are two muscles around hip joint, which are gluteus maximus and rectus femoris muscle in the leg respectively. During the human walking period, the two muscles interact to generate appropriate torque to drive the hip joint to form the right gait. Similarly, there are another two muscles around knee joint, which are shares biceps and vastus medialis muscle. They drive the knee to accomplish the right gait.

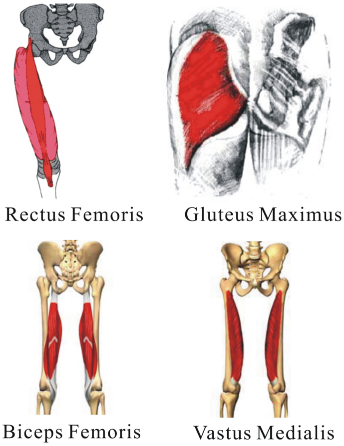

Fig. 3. Lower limb anatomy

Further modification to the mechanical model is introduced:

1) Since the paraplegic patient is suspensory in the locomotor training, so he is partially or mostly unloaded while standing on a moving treadmill. Therefore, the ankle

joint could be neglected in mechanical model because its gait is generated by the motion of treadmill and the exoskeleton leg.

2) During the locomotor training period, because the hip joint of patient only rotates in sagittal plane, so it can be simplied to a revolute joint.

As the analysis above, the fundamental frame of the mechanical model has been defined. The human hip and knee joints can be separately substituted by spherical joint and revolute joint. Two appropriate pneumatic cylinders act as muscles to drive one leg.

2.2 Structure Design

Since the number and DOF of joints on the exoskeleton leg is defined, what should do next is to assign material, dimension to each part and determine the distribution of the cylinders.

The exoskeleton DGO should stand by other principles as below:

1) It should be lightweight for the sake of the patient's comfort. Meanwhile, it should has enough strength. The high rigidity aluminum can meet this requirement.

2) It should be designed length adaptable for every different individual. That is to say, the thigh part must be adjusted in a range of length to accommodate mostly people with different physical size to wear. Adding a translational joint to the thigh part allows the DGO length adaptable.

3) The positioning of actuators should make cylinders provide the maximum torque to drive the exoskeleton legs and cover the physiological space that human legs can reach to. The angle and of joints and the torques needed in the human walking cycle can be consulted in reference [7].

In order to meet this requirement, the kinematic model of mechanical joint must be analysed. As shown in Fig.4, the model is composed of coxa part A, thigh part B and a cylinder.

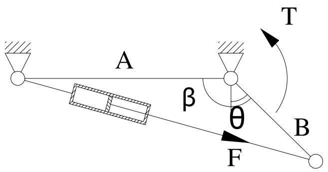

Fig. 4. Kinematic model of a pneumatic driven system

It equals to a four linkage mechanism which is composed of three revolute joint and a translational joint. The kinematic behavior of the leg is described as follows: this motion is actuated by cylinder, while the part A is fixed. Consequently, the part B is driven by the piston of cylinder. The following equation describes the kinematic model:

$$T=\frac{\mathrm{Fgkg}(k\cos\theta\pm\sqrt{1-k^2\sin^2\theta})\mathrm{g}\sin\beta}{\sqrt{k^2+n^2-2kn\cos\beta}} \tag{1}$$

$$n = k\cos\theta \pm \sqrt{1 - k^2\sin^2\theta} \tag{2}$$

$$k = n/l \qquad k \in (0,1) \tag{3}$$

T- output torque of cylinder; *F*- output force of cylinder; *l*- total length of the cylinder; *n*- length of swing link.

The goal of these equations is to find out the most appropriate *k* in order to make cylinder provide the maximum torque.

Fig. 5 shows the torque curves with different *k*. As seen in Fig. 5, when *k* amounts to 0. 55 and 0.65, the cylinders can provide 140Nm and 360Nm torque to the hip joint and knee joint separately at least.

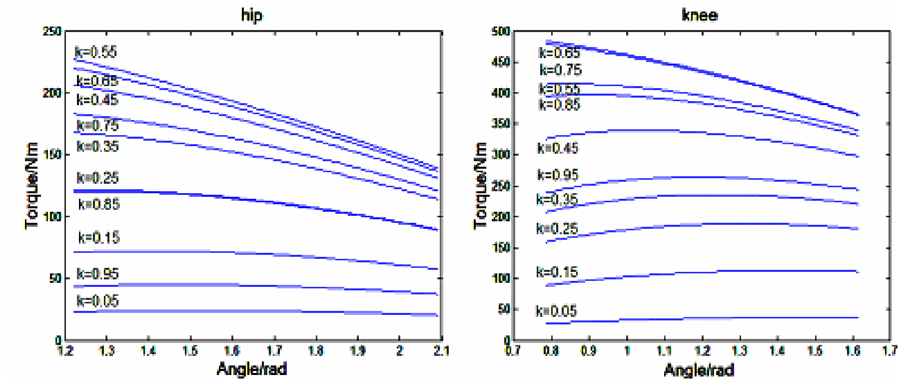

Fig. 5. Output torques of actuator to joints with different *k* in the gait cycle

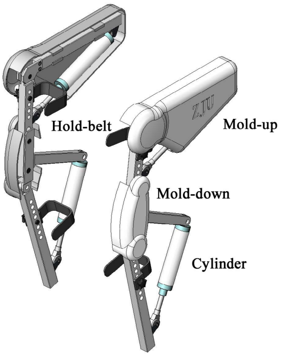

Fig. 6. Conceptual Design of the DGO Frame

Generally speaking, the exoskeleton can support about 155kg weight people at most during the gait cycle according to the computation depicted as above.

Additionally, both hip joint and knee joint can cover the physiological space shown in reference [7] under the determined position of actuators.

According to all analysis as above, the conceptual design of this novel DGO based on exoskeleton leg has been determined, as shown in Fig. 6.

3 Control Architecture

Fig.7 describe the whole control architecture of this DGO.

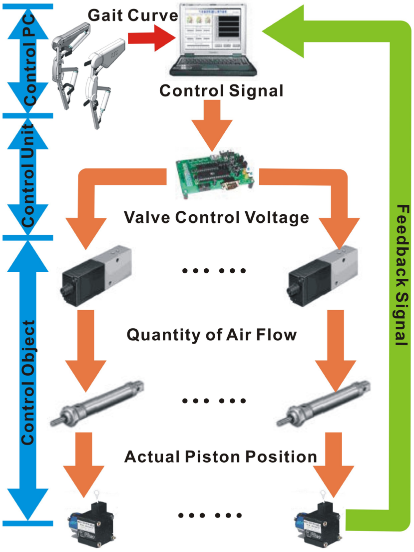

Fig. 7. Control Architecture of DGO

Since air is condensable, low viscosity and lacks of lubricating, the pneumatic system is low rigidity, low responding speed, low system damping ratio and low stability as result to strong nonlinearity. Therefore, it's difficult to control a pneumatic system.

Traditional PID control isn't robust to the nonlinear system. Whereas, fuzzy control is robust to the system for which precise information is not required. However, there are still defects in fuzzy control. Such as that the complexity of fuzzy control increases exponentially when the number of input variables increases.

The hybrid of fuzzy and bang-bang control algorithm takes advantages of the rapid characteristics of the bang-bang and the accuracy near a set point which is guaranteed by the fuzzy allowing the strong nonlinearities to be easily controlled with the precision.

As shown in Fig. 8, the bang-bang controller is used to control the piston when the piston locates far away from the target position whereas the fuzzy controller is applied when the piston is near the desired position. Both the output of fuzzy control and bang-bang are converted to the analog voltage to control the flow through the servo valves.

In fuzzy control, the proper signal output is determined by the position difference (ΔP) and the rate of position difference ($\Delta \dot{P}$). Based on much experiment datum, five levels of ΔP as a input (NF, NM, NS, PM, PF) and six levels of $\Delta \dot{P}$ as the other input (NB, NM, NS, PS, PM, PB) have been determined. After defined these inputs, six levels of the valve control voltage as the output (NL, NM, NS, PS, PM, PL) has been determined. It's reasonable to represent these terms by triangular-shape membership functions, as shown in Fig. 9.

According to the fuzzy variables, fuzzy control rules are defined based on the experiments, as shown in Table. 1.

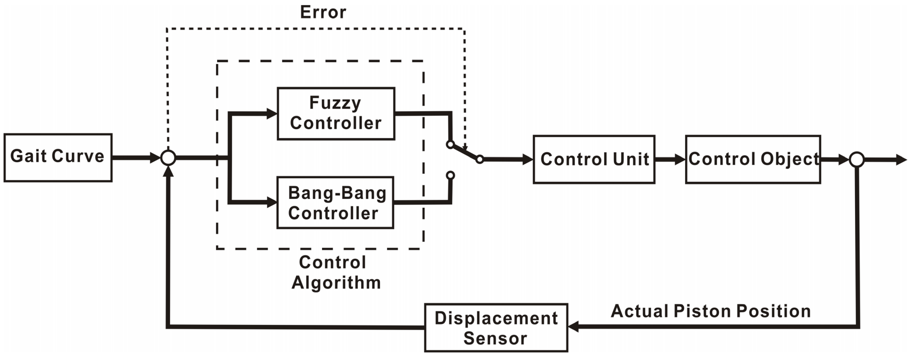

Fig. 8. Block diagram of hybrid control

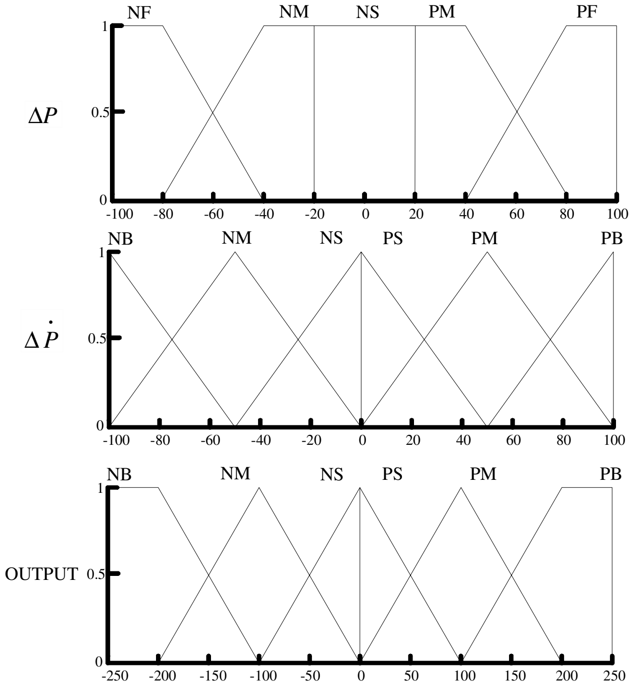

Fig. 9. Membership function of variables

Table 1. Fuzzy rule matrix

Output	The rate of position difference					
Position	NB	NM	NS	PS	PM	PB
NF	PB	PB	PM	PS	PS	PS
NM	PB	PM	PS	PS	PS	PS
PS	PS	PS	PS	NS	NS	NS
PM	NS	NS	NS	NS	NM	NB
PF	NS	NS	NS	NM	NB	NB

In a word, the output of the control system can be depicted by following equation:

$$\text{output}=\begin{cases}\dfrac{\int x\max\left\{\min(m^{i}_{\Delta P},m^{i}_{\Delta\dot{P}})\right\}dx}{\int \max\left\{\min(m^{i}_{\Delta P},m^{i}_{\Delta\dot{P}})\right\}dx} & e\leq a\\ \text{Bang-Bang} & e>a\end{cases} \tag{4}$$

where x is the variable representing valve control voltage characteristic, $m^{i}_{\Delta P}$ is the ΔP membership values at x, $m^{i}_{\Delta\dot{P}}$ is the $\Delta\dot{P}$ membership value at x and a is the setting value according to the experiments.

4 Experiments

Experimental analysis is conducted in order to verify the DGO performance under such conditions as following:

1) DGO works without patient;

2) Set gait is inputted through the LabVIEW operation panel to control algorithm which generates control signal;

3) Displacement sensor (ASM-WS31) acquires the pneumatic piston (FESTO-DSEU-32/40-160) actual position and feed them back to the control system in order to realize a closed-loop control.

Fig.10 shows the prototype of the novel DGO.

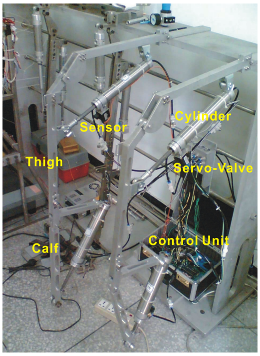

Fig. 10. Prototype of the novel DGO

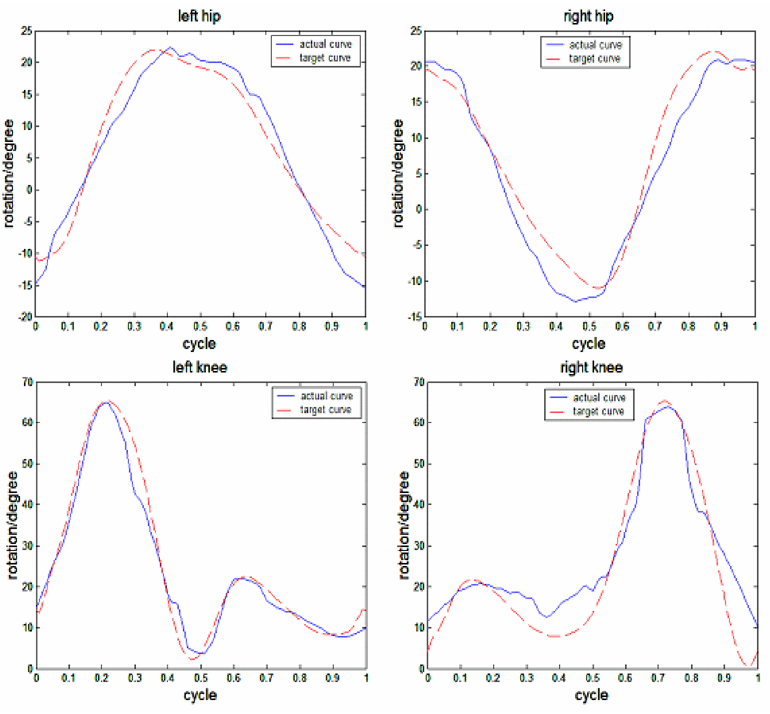

Fig. 11. Contrasts between actual curves and target curves

Fig.11 depicts the contrast between actual curve and target curve of each joint.

Compared with other research groups [4], [5], [6], these curves accord with normal gaits more exactly with less error.

The results from the experiments show that the curves have reached the desired ones approximately. However, error which is about 3~5 degree also exists in the control system. Because pressure of air at one side of the cylinder is never equal to pressure at the other end, the position can not stop immediately. The piston always moves for a while before it stops moving. This unequal pressure problem causes position error in kinematics control pneumatic system. Some compensatory algorithm and modifica-tion could be studied and added to the current one in future work.

5 Conclusion

This research deals with developing a novel DGO based on the pneumatic exoskeleton leg for locomotor training of the paraplegic patient. It takes advantage of pneumatic system and innovates a new way to develop the DGO. The methodology of designing the novel DGO is discussed in detail, and a hybrid of fuzzy and bang-bang control algorithm is employed to realize the desired function. Experiments prove that it's effective for nonlinear control.

Prototype experimental pneumatic DGO is being improved and further modification will be performed. Future experiments will be conducted with the patient load. It should be focused on decreasing error, while increasing the control precision. As the ultimate objective is to transform the prototype DGO to a product which can really used in locomotor training of paraplegic patients.

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