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Adaptive Neuro-Fuzzy Control Based Development of a Wearable Exoskeleton Leg for Human Walking Power Augmentation

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Abstract—**In this paper, a wearable exoskeleton leg conceived and designed to augment human's walking ability is proposed. The ultimate goal of this project is to provide an insight into the methodology of designing and controlling a power assist system, which integrates human's intellect as the central control system for manipulating the wearable anthropomorphic device. The whole process of design, construction and control of a prototype experimental exoskeleton is presented; the feasibility and performance of the novel ANFIS (Adaptive-Network-Based Fuzzy Inference System) based control algorithm are studied followed by the conclusion as well as an outline of anticipated future research.**

I. INTRODUCTION

Integrating humans and robotic machines into one system offers multiple opportunities for creating assistive technologies that can be used in biomedical, industrial, and aerospace applications. A human's ability to perform physical tasks is not limited by intelligence but by physical strength, whereas robotic machines can carry out rigorous tasks such as maneuvering heavy objects easily; at the same time, current artificial control algorithms that govern robots, although highly developed, still cannot achieve the comparable performance to naturally developed algorithms possessed by human. It seems, therefore, that combining these two entities, the human and the robot, into one integrated system under the control of the human, may lead to a solution which will benefit from the advantages offered by each subsystem. This is the underlying principle in the design of exoskeleton systems.

An exoskeleton is an external structural mechanism whose joints correspond to those of the human body. It is worn by the human and the physical contact between the operator and the exoskeleton allows direct transfer of mechanical power and information signals.

Exoskeletons for human performance enhancement are controllable and wearable devices that can increase the strength, speed, and endurance of the operator. The human provides control signals for the exoskeleton, whereas the exoskeleton actuators provide most of the power necessary for performing the task. The human only needs to apply a scaled-down force compared with the load carried by the exoskeleton. [1]

An exoskeleton leg is a wearable device that assists a human to carry a load during walking. The machine is anthropomorphic and is attached at several points along the operator's legs and torso such that the geometry of the human and the machine approximately match each other. [2]

II. RELATED WORK

Since around the 1950s, several exoskeleton leg systems have been studied and developed [3], and can mainly be used for two conceptually different applications, according to which they can be categorized into two types: 1) walking aid for gait disorder persons or aged people; 2) walking power augmentation to travel long distances by feet with heavy loads.

Most of the developed exoskeleton systems fall into the former type. In history, typical systems were a serial of exoskeletons built by M.Vukobratovic *et al*, who initiated research and investigation on exoskeleton and similar structures as rehabilitation orthotic devices in 1967. [4] They developed different models of exoskeletons powered by various actuators, such as hydraulic drivers, pneumatic drivers and DC servo motors. These machines were utilized to verify their theoretic results and the outcome proved to be acceptable. But the obvious drawbacks were the relatively outdated hardware devices and control technologies at that time. Nowadays, the most successful example of exoskeleton used as a walking aid device for gait disorder persons is the Hybrid Assistive Leg (HAL) developed by Yoshiyuki Sankai *et al.* Sensors such as angle sensors, EMG (ElectroMyogram) sensors and floor reaction force sensors are adopted in order to obtain the conditions of the HAL and the operator. With all of the motor drivers, measurement system, computer, wireless LAN (local area network), and power supply built in the backpack, HAL works as a completely wearable system. HAL has a hybrid control system that consists of autonomous posture controller and power assist controller based on biological feedback and predictive feedforward. [5]

In the latter type, users aided by the exoskeleton can carry more and walk longer before feeling tired if compared to those without the exoskeleton system. The initial intention of these powered structures was, in fact, to enable normal man to perform overloaded tasks, especially in military applications. Currently, the system might provide soldiers, fire fighters, disaster relief workers, and other emergency personnel the ability to carry major loads such as food, weaponry, rescue

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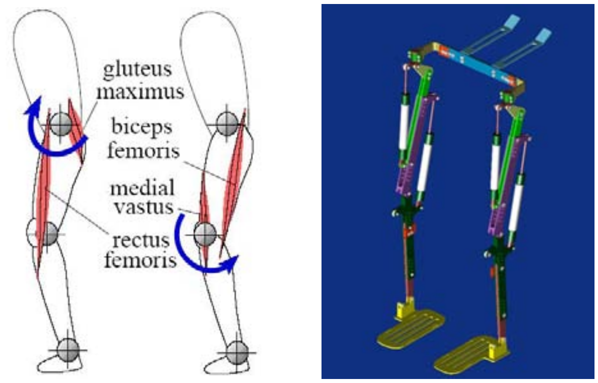
equipment, and communications gear with minimal effort over any type of terrain for extended periods of time. One of the rarely published results from this area was the well-known Hardyman by General Electric, built as prototype and tested in 1968. It was solved as a master-slave follower system, with electric actuators at the joints. The project was finally abandoned for lack of interest by potential users. [4] Some latest research results in this area come out of the BLEEX (Berkeley Lower Extremity Exoskeleton) project by Homayoon Kazerooni, who has been directing his research team in the Human Engineering Laboratory of UC. Berkeley to develop a DARPA (Defense Advanced Research Projects Agency) funded exoskeleton since the year 2000. The primary objective of the project is to create a self-powered exoskeleton for human strength and endurance enhancement that is ergonomic, highly maneuverable, mechanically robust, lightweight and durable. In November 2003, the first completely functional prototype experimental exoskeleton was demonstrated, which is comprised of two powered anthropomorphic legs, a power unit, and a backpack-like frame on which a variety of loads can be mounted. More than 40 sensors, including some that are embedded within the shoe pads, and hydraulic actuators form a LAN for the exoskeleton and function much like a human nervous system. The exoskeleton uses a state-of–the-art small hybrid power source, which delivers hydraulic power for locomotion and electrical power for the exoskeleton computer. Wearing the exoskeleton, the operator can carry significant loads over considerable distances without reducing his/her agility, thus significantly increasing his/her physical effectiveness. As scheduled, a fully integrated prototype powered by hydrogen peroxide is to be demonstrated in 2005.

III. MECHANICAL STRUCTURE

What we desire is to invent a machine that could successfully assist human to cover longer distances for longer periods with over-mounted loads on a physical interface basis, which translates into a number of design specifications. Therefore, in order to achieve an ideal performance, we design the structure of the exoskeleton leg according to the following principles:

1) The exoskeleton should be anthropomorphic and ergonomic, not only in shape but also in function. On the one hand, it should be analogous to the human lower limb in the case of joint positions and distribution of degree-of-freedoms (DOFs); on the other hand, the actuators in the exoskeleton leg should be allocated in the corresponding position to the representative muscles in human leg, in order to simulate the function of the muscles during the process of human walking. In the meantime the number of actuators and sensors should be limited as much as possible to increase the robustness and reduce the cost of the leg. Under these circumstances can we establish the premise on which the expected exoskeleton can move in concert with the operator with minimal interaction force between the two.

2) The exoskeleton structure should be length adaptable. That is to say, both the upper and lower parts of the metal leg can be adjusted in a broad range of length, thereby accommodating average people with different physical statures to strap on.



(a) (b)

Fig.1. Design of Exoskeleton Leg from Human Leg Model
(a) Representative Muscles for Motion of Hip and Knee
(b) Structure of the Exoskeleton Metal Frame

3) The exoskeleton should be firm and lightweight. The metal structure of the exoskeleton has to support heavy loads mounted on its backpack-like frame and suffer from impact from ground during walking. So stiffness of the structure should be ensured. Besides, as our design objective is to build a self-contained device, which means it has to carry its own energy supply and controller other than various regular equipments, therefore the entire exoskeleton should be as light as possible to increase its ability of mounting payload as well as to obviously afford facilities for easier operation.

The remainder of this section will detail the simplified model of the human leg, based on which the process of designing an anthropomorphic leg will be addressed.

A. *Human Leg Model*

There are three joint articulations in the human leg: hip, knee and ankle, around which groups of muscles contract synergically to generate the torque activating various rotary movements. Flexion/extension, adduction/abduction, lateral rotation/medial rotation constitute the 3 DOFs of the hip joint; similarly, the ankle joint owns these 3 DOFs as well, whereas the knee joint is only able to rotate in the sagittal plane like a revolute joint. Biomechanical models of the leg which stand for precise anatomical models including muscles, tendons and bones are too complex to be used in mechanical design of an anthropomorphic exoskeleton leg. A most suitable and simplified model is depicted in Fig.1 (a), in which we select the rectus femoris and gluteus maximus to represent the muscle group around the hip joint, and meanwhile biceps femoris and medial vastus act as the most representative muscles in the group around the knee.

B. *Exoskeleton Leg Design*

Based on the foregoing human leg model, an exoskeleton leg is designed with the following specifications taken into consideration. (Fig.1 (b))

1) Joints and DOFs: Because the goal is to create a bipedal walking machine, it is only logical to study how human successfully performs the task. The interest in this study is mainly focused on the motions of the legs and the feet in the

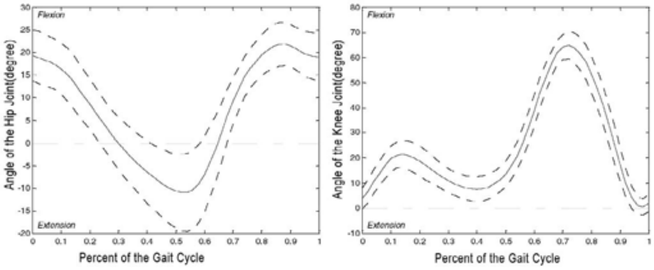


Fig.2. Joint Trajectories of Hip and Knee in Sagittal Plane during a Single Gait Cycle

sagittal plane. The other motions of the legs and motions of the rest of the body are mainly for balance, momentum conservation, and energy storage. These tasks are not assigned to the legs of this machine; thus, the human leg motions that accomplish them are not considered. [7] So the designed exoskeleton frame features three revolute joints in the correspondent positions of the three joint articulations to realize their flexion and extension movements in the sagittal plane. In addition, in order to improve its flexibility and facilitate turning around during walking, one more revolute joint is also located in the proximal portion of the hip joint, making the lateral and medial rotation of the thigh become convenient. Altogether, there are 8 DOFs in the whole structure: two in the hip, one in the knee and one in the ankle distributed respectively in each leg.

2) Positioning of Actuators: To adequately simulate the muscle activity during walking for the aim of building an anthropomorphic leg, positioning of actuators should be carefully considered. Referring to Fig.1 (a), actuators should be employed in the place of the representative muscles, assisting them to accomplish the motions of hip and knee. Therefore, we adopt one actuator to simulate the function of rectus femoris, and another one to simulate biceps femoris.

3) Stroke of Actuators: Motion range of each actuator can be determined by the swing scope of its corresponding joint. According to the statistic data of human kinematics, the angle of the hip joint varies in a range about 50 degrees, between 30 degrees of flexion and 20 degrees of extension with the angle in the position of standing straight set as zero; as to the knee, the joint can only flex to the maximal angle of 70 degrees or so. Fig.2 shows the mean and standard deviations, by medical data from anatomical markers in limb segment [8], for joint angles of the hip and knee motion during one gait cycle. Through calculation utilizing these data, suitable actuators with proper strokes can be selected to fulfill the desired tasks: to simulate their muscular counterparts.

4) Stature Compatibility: As a rule, the length ratios of different parts of the human body are relatively fixed. Table I lists the general dimension data of human body, in which the percentage of each part of the human leg to the whole body is presented. [9] Based on these data, the distances between the three joint articulations are determined. As we want to enable different statured people to operate the machine, therefore the lengths of thigh and shank should be adjustable. Through calculation, the length variance of thighs or shanks for people with the stature from 160cm to 180cm turns out to be approximately 6cm. Consequently, we design the thigh or the shank able to be lengthened and shortened in the range of 6cm with the relative movements of its inner part and outer part in the similar way a prismatic joint goes. Likewise, the breadth of the waist structure which connects the two legs on either side can also be regulated to suit people with different waistlines. For comfortable wearability, the metal structure is strapped onto human body at waist, shanks and feet, where soft pads and strips are attached to protect the operator and provide him/her an agreeable experience.

TABLE I
HUMAN BODY DIMENSION DATA

Human Body	Ratio (%)
Stature	100
Leg Length	53.0
Hip to Knee	24.5
Knee to Ankle	24.6
Ankle to Sole	3.9

IV. CONTROL STRATEGY

While there are many important aspects in successfully developing an exoskeleton, efficient control strategy and actuation scheme are critical. A successful overall approach must emphasize the optimization of control efficiency, both at the decision-making level and at the execution level.

Generally speaking, for the control of autonomous biped walking robot, a hierarchical control scheme is commonly adopted, which comprises three levels: walking planning, gait synthesis and joint control, as shown in Fig.3. The walking planning level deals with walking planning, obstacle crossing and gait selection. The gait synthesis level receives constant values such as the step length, walking speed, maximum foot lift magnitude and so on from the upper level, and then repetitively generates reference commands for each joint controller. [10]

The salient feature of a human-operated exoskeleton, which is also the most remarkable difference between exoskeleton and biped robot, is the participation role of human in the process of control and decision-making. As stated previously, the design of exoskeleton is grounded in the notion that combining the skills of the human and the exoskeleton, and allowing each one to perform the tasks they are good at can simplify the design and improve the exoskeleton's effectiveness. The tasks that we can assign to the operator without causing excess mental or physical

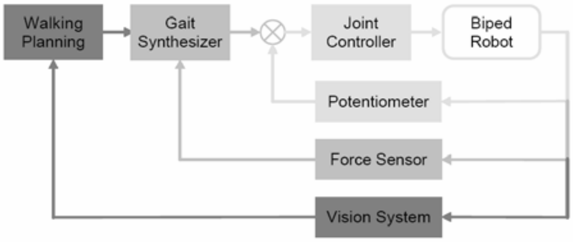


Fig.3. Hierarchical Control System of Biped Robot

fatigue are navigation and balance, which still remain to be the most intractable problems in biped robotics till now, notwithstanding many artificial intelligent control technologies developed. [7] That is to say, by introducing human as part of the control system, the tasks in the outmost level in Fig.3 can be easily undertaken by human instead of some complex artificial controller and vision system.

In the following subsections, we will enter into details the characteristics of the novel control system adopted by the exoskeleton leg, which are arranged as follows: four principles to design the system, three levels to implement it and two steps to operate it.

A. Four Principles

1) Minimizing Disturbances: The exoskeleton is wrapped around the operator to provide the mechanical interface between the two and support the payload as well as its own load, so the proposed control algorithm should pursue the objective that minimal disturbance is exerted on the operator to ensure user comfort while the operator and the exoskeleton are walking concertedly. That implies actuators should be controlled smoothly and swiftly to generate a target gait that is much close to a natural one.

2) Lowering System Complexity and Cost: Number of actuators and sensors should be optimized to a reasonable value. Obviously, there is a significant advantage in reliability enhancement as well as weight and cost savings in using passive joints where appropriate as opposed to actuated joints to simplify the system, because the addition of an actuated degree of freedom will obviously increase the overall complexity of the control system. In the case of sensors, the more ones we install and the more elaborate the sensor is, the better understanding we can certainly obtain of the system. But out of the trade-off of control effect and system cost, we also prefer a reasonable choice.

3) Learning Ability Needed: It is known that every normal person shares the common characteristic of walking, as shown in Fig.2, but after a careful observation, we can easily find that actually each person owns his/her particular walking habit, which means it is true that joint trajectories of normal people are contained in the area between the two dashed lines, but each specific trajectory curve is surely distinct from the others. Thus, if the trajectory of the exoskeleton is preset to a fixed one, the operator has to be forced to accommodate himself/herself to the fixed walking mode, which will undoubtedly lead to unease and fatigue easily due to the interaction. For the sake of concerted and comfortable walking, the exoskeleton should be able to produce a customed gait that is almost identical to the operator's. Consequently, the control system should possess the ability of being trained to master the operator's gait trait and playbacking it in phase the same time the operator piloting the device.

4) Simplifying Control Strategy: Designing an intelligent controller can endow the exoskeleton with learning ability, but how to trigger a proper posture at the proper time still waits to be resolved. Two basic control approaches are usually employed in the operation of exoskeleton typed devices. One is based on controlling the exoskeleton to track the human operator joint by joint. The alternative approach is based on tracking the limb extremity, i.e. the foot for exoskeleton leg, but not necessarily matching each joint. As joint-by-joint tracking implies a position-position control loop, position sensing of both the human and exoskeleton joints will also be required. In addition, replicating some types of joints mechanically is difficult, and the likely result is tracking errors. The second approach eliminates the need to accurately sense the position of each human joint and the leg will be controlled based on the force input at the extremities as opposed to matching positions of each joint. Hence significant reduction in mechanical complexity is achieved in this approach at the expense of increased complexity of the control system. [11] In order to achieve a good control performance and simplify the control strategy, we would make use of some kind of sensed signal, which should be able to be easily acquired and have apparent recurrent characteristics, as the trigger to be input into the intelligent controller to determine a unique output, which comprises the displacement reference signals for actuators collaborating to produce a specific posture. Superior to the conventional approaches, an optional ideal control algorithm is to establish directly the relationship between a sensor signal and the actuation signal, thereby simplifying the control system significantly and eliminating the possibility of error accumulation.

B. Three Levels

In accord to the block diagram in Fig.3, the control system of the exoskeleton device also features a similar hierarchical framework. It consists of three levels detailed in the following parts and the controller of each level is indicated in the bracket respectively.

1) Walking Planning Level (Human): By taking advantage of the intelligence of the operator, the complexity of bipedal walking machine is reduced to a tractable problem. Human, as the most sophisticated controller, will be competent for dealing with intricate tasks such as walking planning and navigating, obstacle avoiding or crossing and balance keeping. While these problems for autonomous biped robots are still active research areas, their application to an exoskeleton is almost negligible because these capabilities of the human operator can be transferred to the exoskeleton. Of course, besides the above mentioned tasks, the primary work of human is to walk, thereby supplying a periodic input signal into exoskeleton's subordinate control loops. We select the *Plantar Pressure Signals* (PPS) at balls and heels of the both feet, which are easily acquired via pressure sensors and vary recurrently and regularly with noticeable features (see Fig.4), as the reference signals to trigger correspondent actions of actuators.

2) Gait Synthesis Level (Computer): In this level, a novel intelligent control algorithm is implemented in a portable personal computer, which takes the PPS gathered through a data acquisition (DAQ) card as the input and after gait synthesizing, outputs the command to the position control loops distributed in the actuators and controlled by

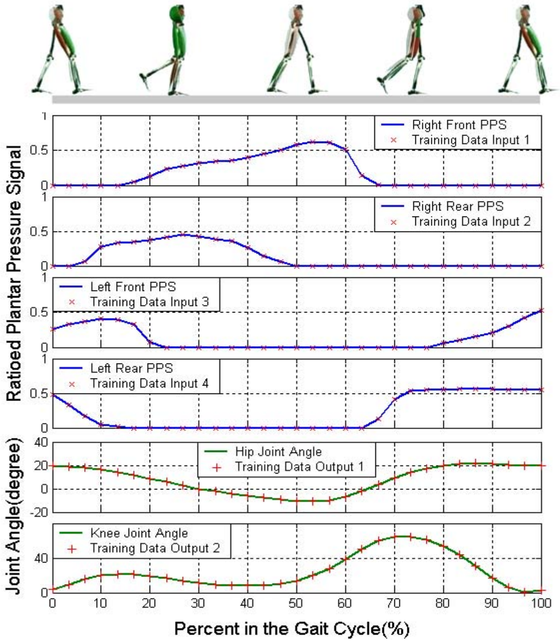
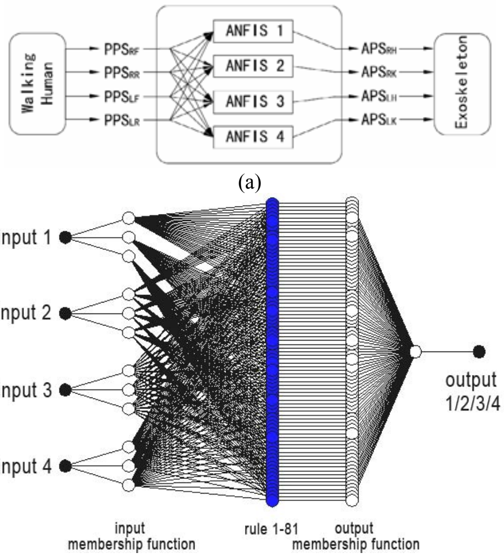


Fig.4. Plantar Pressure Signals and Joint Angles of Hip and Knee in Right Leg during a Single Gait Cycle and Input/Output Data Pairs for ANFIS

microcontrollers in a host-client manner. The relationship between PPS and positions of actuators is completely nonlinear and turns out to be multi-input-multi-output (MIMO), so conventional control algorithms cannot guarantee an effective and efficient solution.

ANFIS, which stands for Adaptive-Network-Based Fuzzy Inference System, or semantically equivalently, Adaptive Neuro-Fuzzy Inference System [12], installs the fuzzy system in an architecture similar to neural networks. It is a multi-layer network with each node performing a function such as to make the entire network equivalent to a fuzzy system. This network interpretation of the fuzzy system allows for the modification of parameters using gradient descent and least square estimate learning algorithms. ANFIS can learn fuzzy rules from input/output data pairs, incorporate prior knowledge of fuzzy rules, fine tune the membership functions, and act as a self-learning fuzzy controller by automatically generating the fuzzy rules needed.[13] As regards application in the exoskeleton, it does not require detailed kinematic or dynamic model and can automatically derive the fuzzy rules from stipulated input/output data pairs, namely PPS and APS(Actuator Position Signal), self-tune the fuzzy rules and make the exoskeleton learning and walking with proper gait. As we need to actuate simultaneously four pneumatic cylinders located at right hip, right knee, left hip and left knee respectively, therefore altogether four ANFIS controllers should be constructed with different fuzzy rules derived and tuned to fulfill different tasks, as shown in Fig. 5(a). Detailed structure of a single ANFIS controller is shown in Fig. 5(b), in which three input membership functions are assigned to each input PPS(right front, right rear, left front and left rear), thereby totally 81 rules established to generate one APS output. The number of input membership functions is determined in consideration of computing efficiency and system complexity. A model made up of too few fuzzy rules will be definitely insufficient to reflect the real system, whereas too many rules will result in a redundant model, which cannot simulate the original system either.



(a)

(b)

Fig.5. (a) Structure of Gait Synthesis Level
(b) Structure of a Single ANFIS Controller

3) Joint Control Level (Microcontroller): Out of question, it is more than vital to select an appropriate actuation scheme at the execution level. Compared to other driving methods, pneumatic actuators offer the following advantages for positioning applications: 1) low cost; 2) high power-to-weight ratio; 3) ease of maintenance; 4) cleanliness; and 5) a readily available and cheap power source. A particularly suitable application for pneumatic actuators is the position control of robotic manipulators, where stiff and lightweight structures, flexible actuation and swift response are critical. Unfortunately, pneumatic actuators are subject to high friction forces, deadband (due to stiction), and dead time (due to the compressibility of air). These nonlinearities make accurate position control of a pneumatic actuator difficult to achieve even using expensive proportional servo valves and pressure sensor feedback loops. A preferable scheme is to select inexpensive, compact and lightweight on/off solenoid valves rather than bulky servo valves, to develop a fast, accurate, and low-cost pneumatic actuator system, where control problems such as dead band and stiction can be reduced significantly in the Pulse-Width Modulation (PWM) control manner. [14] A typical position servo control system in this fashion is symbolically depicted in Fig.6.

As we stated, although there are 4DOFs in each leg, there is no need to actuate them all. In view of the primary contribution to walking of hip and knee's movements in sagittal plane, we manage to actuate them by pneumatic cylinders with the rest ones left passive.

C. Two Steps

The usage of this walking assisting machine is divided into two steps: Initially, the human operator has to train the machine the way to walk; afterwards the exoskeleton can supply power assistance to its operator in return.

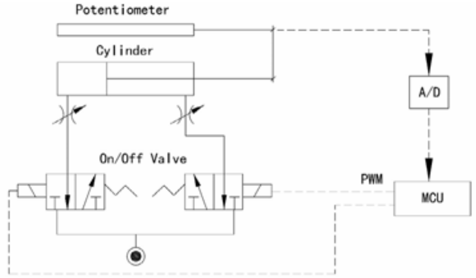


Fig.6. Schematic Diagram of a Pneumatic Position Servo System Using On-Off Solenoid Valve.

1) Training Step: Training the exoskeleton involves the operator strapping on it and towing it to walk with no pressured air supplied to the cylinders for several gait cycles, enabling the PC to record the operator's PPS and signals of potentiometers attached by each cylinder. Next, the ANFIS controller will construct the input/output mapping based on the data pairs. Once the relationship established, the walking particularity of the operator can be mastered by the intelligent exoskeleton.

2) Assisted Walking Step: After being trained, the exoskeleton can be powered to walk, forming a gait similar to its operator's according to the instantly measured PPS. Although the operator may feel a little bit tired bearing the unpowered metal leg in the former step, as a return, he/she can still stay energetic after carrying major loads over a long distance for extended periods of time, as seems to be worthwhile in the long run.

V. SIMULATION

In order to verify the feasibility of the ANFIS based control approach prior to applying it practically, we manage to simulate the control effect in software environment. Without loss of generality, we selecte 31 sets of training data in the PPS curves and joint angle curves (Fig.4) respectively at same intervals in the entire spectrum of gait cycle as input/output data pairs. After self-learning, the ANFIS controller outputs two generated curves for the two joints, as shown in Fig.7. The curves are comparatively smooth and almost identical with the original joint trajectories, indicating that using the four pressure signals as input to infer a position output is a practical proposal and the control performance is satisfactory as well.

VI. CONCLUSION AND FUTURE WORK

In this research, we are devoted to developing a wearable exoskeleton leg for augmentation of human walking ability, which incorporates human as the integral part of the control system and can relieve human's physical fatigue caused by excessive walking by feet. The methodology of designing an anthropomorphic and adaptable exoskeleton leg is discussed, and a hierarchical control system is employed to realize the desired function. In particular, a control strategy based on ANFIS controller is explored, which directly associates the plantar pressure to the displacement of pneumatic cylinder and proves to be convenient and efficient by software simulation.

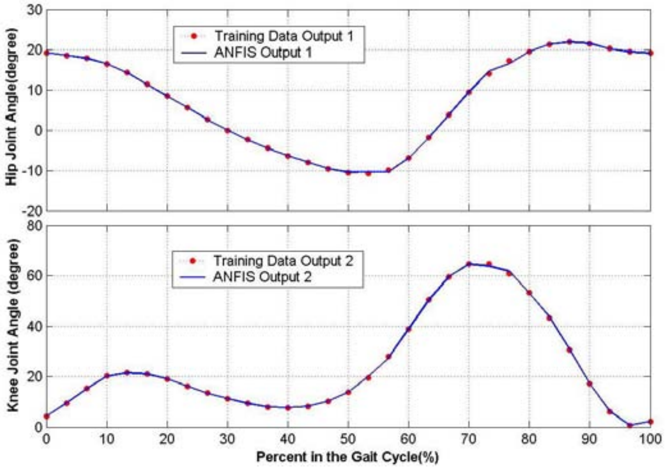


Fig.7. Training Data Output and ANFIS Controller Output

Prototype experimental exoskeleton is being constructed and further experiments will be performed. Future work will be mainly focused on building a more lightweight, compact, comfortable and flexible exoskeleton, and improving the control algorithm to be more robust and adaptable to various conditions. As the ultimate objective is to build an untethered and fieldable device, so a mountable power generation subsystem will be a more challenging issue for such a mobile application.

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