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Development of Body Weight Support Gait Training System using Pneumatic McKibben Actuators

~Control of Lower Extremity Orthosis~ *

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Abstract— **Recently, robot assisted therapy devices are increasingly used for spinal cord injury (SCI) rehabilitation in assisting handicapped patients to regain their impaired movements. Assistive robotic systems may not be able to cure or fully compensate impairments, but it should be able to assist certain impaired functions and ease movements. In this study, the control system of lower extremity orthosis for the body weight support gait training system which implements pneumatic artificial muscle (PAM) is proposed. The hip and knee joint angles of the gait orthosis system are controlled based on the PAM coordinates information from the simulation. This information provides the contraction data for the mono- and bi-articular PAMs that are arranged as posterior and anterior actuators to simulate the human walking motion. The proposed control system estimates the actuators' contraction as a function of hip and knee joint angles. Based on the contraction model obtained, input pressures for each actuators are measured. The control system are performed at different gait cycles and two PMA settings for the mono- and bi-articular actuators are evaluated in this research. The results showed that the system was able to achieve the maximum muscle moment at the joints, and able to perform the heel contact movement. This explained that the antagonistic mono- and bi-articular actuators worked effectively.**

Keywords—Mono-articular actuators, bi-articular actuators, pneumatic artificial muscle, and contraction model based controller.

I. INTRODUCTION

The needs for the medical and rehabilitation technology were increased with the increase numbers of old people and decrease numbers of young labors. Furthermore, lack of people's welfare places also contribute for the needs of medical and rehabilitation technology. These facilities are essential to lessen the burdens for the doctors. Moreover, it's also eases the handicap people, old people and helpers physically and mentally. This research focuses on the control system for legs orthosis of the developed Body Weight Support Gait Training System [1, 2]. This system aims was the assistive rehabilitation gait training for the spinal cord injury (SCI) patient that suffer the lower limb disability either one side or both side of their legs. The developed system was implemented PAM actuators and has a complex and non-linear system. However, its control system which implemented proportional directional control valve was rather poor.

Based on the previous researches, it is possible to use a standard PID controller in a feedback loop to control the joints' angle of the assistive robotic towards their desired values. Nevertheless, without additional model or integrated controller, it is not able to control compliant robots accurately due to the complex and highly nonlinear dynamics of the PMA, thus the resulting position was rather poor. There are lots of established controller design which are used to control this muscle actuator such as; Caldwell (1993~1995), tested a feed forward PID regulator and developed an adaptive controller for the pneumatic artificial muscle (PAM) manipulator; Repperger (1999) handled the nonlinear factor with a nonlinear feedback controller using a gain scheduling method; Tondu, and Lopez (2000) employed sliding-mode control approach; Folgheraiter (2003) developed an adaptive controller based on the neural network for the artificial hand; Balasubramanian, and Rattan (2003) proposed feed forward control of a nonlinear pneumatic muscle system using fuzzy logic; Ahn, and Tu (2003~2005) proposed an intelligent switching control scheme using a learning vector quantization neural network and a nonlinear PID control to improve the control performance of PAM manipulator using neural network (NN). However, using a complicated control algorithm does not always indicates the best solution that can be used. Rather than using a very complicated algorithm for the system, a much simpler approach is to be proposed.

II. SYSTEM OVERVIEW FOR THE LOWER LIMB ORTHOSIS

Figure 1 shows the developed Body Weight Support Gait Training system used for this research. This system used six PAM actuators which arranged as antagonistic (posterior and anterior) mono-articular and bi-articular actuators based on the human musculoskeletal system. The PAM used in this research is the McKibben artificial muscle actuator, which was assembled manually in our laboratory. It is constructed using a rubber tube which is braided with braiding strips. The input pressures of the PAMs are regulated by electro-pneumatic regulator. The increase in air pressure will cause the internal rubber tube to expand, but the outer layer which is the braiding will suppress the tube elongation. In other words, the PAM actuators can imitate the force and muscle

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contractions of humans' muscle. The PAM's movement principal is almost similar to the human muscles' principle and might be able to perform similar contractions and expansions. The hip and knee joint control angles are measured using potentiometers. This system uses the xPC-Target toolbox to exchange the information signals and output data between the host PC and the target PC. Control program is coded in the C language using the MATLAB/Simulink software.

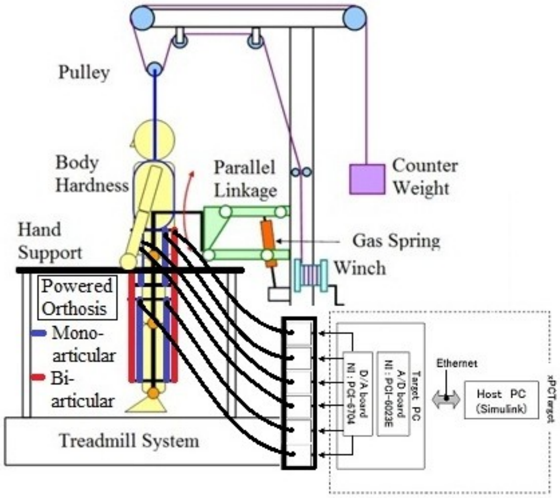


Figure 1: Overview of control system.

III. METHODS

The antagonistic PAM actuators' contraction of the lower limb orthosis is determined using the coordinates system. Then, a control system which estimates the antagonistic PAM length (contraction) from the hip and knee joints' angle is constructed. Based on the PAM's contraction equation, the pressure input pattern for each actuators are determined. Two tests are performed in this experiment; first, with the antagonistic mono-articular PAMs alone; and second, is with the addition of antagonistic bi-articular PAMs. Each test is evaluated with different gait cycles of 3, 4, and 5 seconds for five cycles of the human's natural gait trajectory [11]. Moreover, two position settings of the PAMs are performed for both tests as can be seen in Figure 8. In total, we performed four tests for the control system; first, mono-articular setting (PAM setting 1); second, mono-articular setting (PAM setting 2); third, mono- and bi-articular setting (PAM setting 1); and fourth, mono- and bi-articular setting (PAM setting 2). The control system is evaluated using the percentage [%] of gait cycle.

IV. PNEUMATIC ARTIFICIAL MUSCLE'S CONTRACTION MEASUREMENT

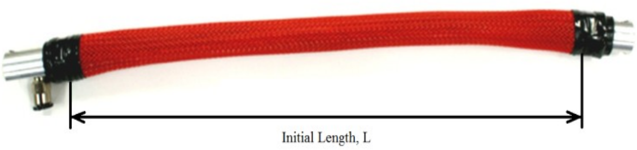


Figure 2: Pneumatic artificial muscle (PAM) - McKibben.

Figure 2 shows the pneumatic muscle actuator (McKibben) with diameter of 1.0 [inch] which is used as the sample to evaluate the PMA's contraction percentage with the input pressure as the variable. The behavior of PAM with regards to its shape, contraction and tensile force when inflated depends on the geometry of the inner elastic part and the braid at rest and on the materials used (Tondu 2000). Maximum force of approximately 800[N] at 0.5[MPa] can be generated from this muscle actuator without load condition. Figure 3 shows the experimental setup used for the measurements. Three samples of the PMAs with different initial lengths, L of 300, 450, and 600 [mm] are used for the measurements. These PMAs' actuator are evaluated at different pressure inputs of 0.1, 0.2, 0.3, 0.4, and 0.5[MPa] for the unloading condition to determine its' contraction characteristics. Further measurement is also conducted for a pressure under 0.1[MPa].

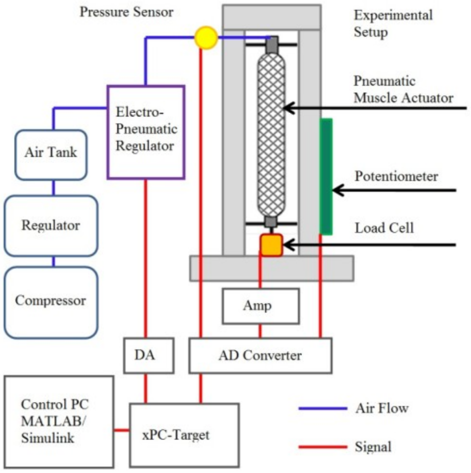


Figure 3: Experimental Setup.

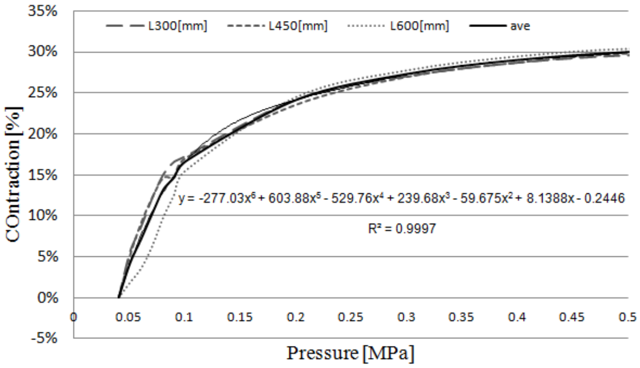


Figure 4: Contraction measurements.

Based on the results in Figure 4, it shows that the PAMs' contraction gives an approximately similar value, converging at 30% of muscle contraction. The result is represented using the average value of the PAMs contractions with 6th order-polynomial function and high approximation of (R^2=0.9997). This function is introduced into the control system to determine the input pressure for each of the mono- and bi-articular actuators.

V. CONTROL SYSTEM FOR THE LOWER LIMB ORTHOSIS

Figure 5 shows the antagonistic mono-articular and bi-articular PAM actuators maximum and minimum allowable range for its arrangement. In order to reduce the moment of inertia, the orthosis was set symmetrically in the longitudinal direction. The PAM's location in the coordinate system is obtained from the model simulation which was programmed using the MATLAB/Simulink. This model is actuated based on the reference input angle of hip and knee joints. The changes in length of the PAMs from the simulation provide the co-contraction data for the mono- and bi-articular actuators. Then, these data is obtained using the coordinate's equation as can be seen in Figure 6.

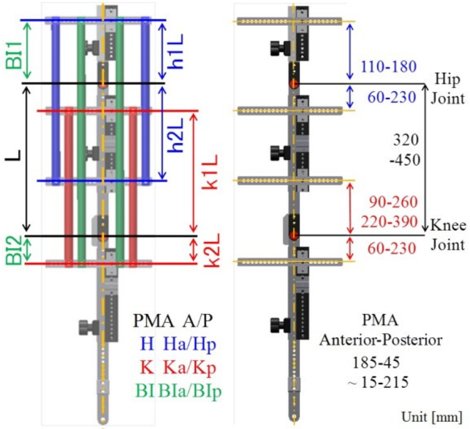
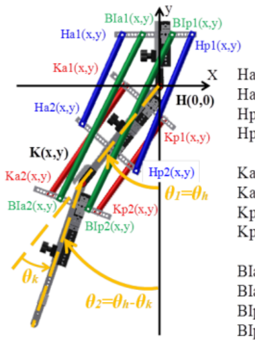


Figure 5: Range of position configuration for PAMs and orthosis system.



$Ha1(-Ha, h1L)$
$Ha2(-Ha\cos\theta_1 - h2L\sin\theta_1,\ Ha\sin\theta_1 - h2L\cos\theta_1)$
$Hp1(Hp, h1L)$
$Hp2(Hp\cos\theta_1 - h2L\sin\theta_1,\ -Hp\sin\theta_1 - h2L\cos\theta_1)$

$Ka1(-Ka\cos\theta_1 - (L-k1L)\sin\theta_1,\ Ka\sin\theta_1 - (L-k1L)\cos\theta_1)$
$Ka2(-L\sin\theta_1 - Ka\cos\theta_2 - k2L\sin\theta_2,\ -L\cos\theta_1 + Ka\sin\theta_2 - k2L\cos\theta_2)$
$Kp1(Kp\cos\theta_1 - (L-k1L)\sin\theta_1, -Kp\sin\theta_1 - (L-k1L)\cos\theta_1)$
$Kp2\ (-L\sin\theta_1 + Kp\cos\theta_2 - k2L\sin\theta_2,\ -L\cos\theta_1 - Kp\sin\theta_2 - k2L\cos\theta_2)$

$BIa1(-BIa, BI1)$
$BIa2\ (-L\sin\theta_1 - BIa\cos\theta_2 - BI2\sin\theta_2,\ -L\cos\theta_1 + BIa\sin\theta_2 - BI2\cos\theta_2)$
$BIp1(BIp, BI1)$
$BIp2\ (-L\sin\theta_1 + BIp\cos\theta_2 - BI2\sin\theta_2,\ -L\cos\theta_1 - BIp\sin\theta_2 - BI2\cos\theta_2)$

Figure 6: PAM's configuration coordinate system.

By using the equation obtained in Figure 4, the PAMs' contraction data are converted into input pressures for each of antagonistic mono- and bi-articular actuators. Based on this method, the inputs for actuating the lower extremity orthosis are determined. PID controller is used for correcting the required input pressure for each actuator. Output data is measured using potentiometers. Figure 7 shows the control system schematic diagram for the gait training system.

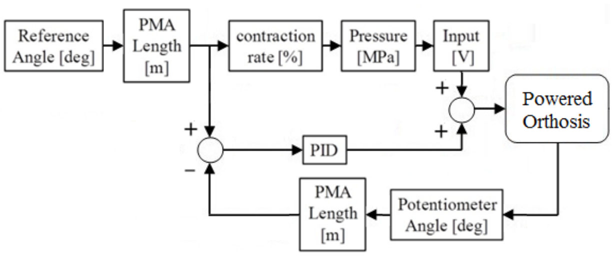


Figure 7: Control system schematic diagram.

VI. EXPERIMENT SETUP

The required software and hardware for this gait training system experiment is showed in the previous section (see Figure 1). There are two tests for this experiment which is with the antagonistic mono-articular PAMs alone, and with the addition of antagonistic bi-articular PAMs. Each test is performed with gait cycles of 3, 4, and 5 seconds for five cycles of the human walking motion. The hip and knee joint angles data of the leg orthosis are collected for the performance analysis. There are two PAM position settings which are considered for the test as can be seen in Figure 8, and the best position setting is determined based on the gait cycle performance. We performed the tests using four different settings; first, mono-articular setting (PAM setting 1); second, mono-articular setting (PAM setting 2); third, mono- and bi-articular setting (PAM setting 1); and fourth, mono- and bi-articular setting (PAM setting 2).

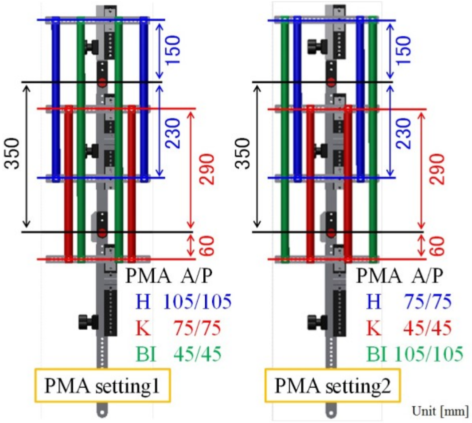


Figure 8: PAM's position for the orthosis system.

VII. RESULTS AND DISCUSSIONS

In this study, the control system which implements the PAM's contraction model and equation (Figure 4) is proposed to control the input pressure of the antagonistic mono- and bi-articular actuators. This control system controls the hip and knee joints' angle of the leg orthosis in a co-contraction movement.

Figure 9 shows the hip angle control for the tests with mono-articular actuators alone, and with the addition of bi-articular actuators, both for PAM settings 1 and 2. In addition, Figure 10 shows the knee angle control with the same PAM settings. For the hip angle control performance (Figure 9), the result shows that, we are not able to achieve the maximum muscle moment (flexion) by using the mono-articular PAM actuators alone. However, when we tested the control system with the addition of bi-articular PAM actuators, there is an improvement in hip angle control for both of the tests with PAM settings 1 and 2. Moreover, the performance for the knee angle control also shows an improvement as can be seen in Figure 10. The result shows that we are not able to achieve the maximum muscle moment (flexion) and unable to get smooth heel contact movement at knee joint by using the mono-articular PAM actuators alone. However, when we implement the gait training system with the addition of bi-articular PAM actuators, we were able to achieve the maximum knee angle extension as well as smoother movement during the heel contact position for both PAM settings.

The comparison of mono-articular and bi-articular actuators' range of motion shows that, bi-articular PAMs has wider range of motion and are able to generate a greater force. As a result, this enables the orthosis system to achieve the high muscle moment which cannot be obtained by using mono-articular actuators alone. The addition of bi-articular actuators works as a muscle support system that provides the orthosis system with greater actuation power and smoother movement at the joints including the heel contact position. When we consider the result of the hip and knee angles (with addition of bi-articular PAMs), its range of motion is sufficient to simulate the human's walking motion with little time delay. In the single support phase of the gait cycle 10-30 [%], sufficient bending at the knee joint was achieved during the heel contact movement which is difficult to obtain using mono-articular PAM actuators alone for both PAM settings. However, if we try to shorten the gait cycle and time delay, the inertia effect becomes evident.

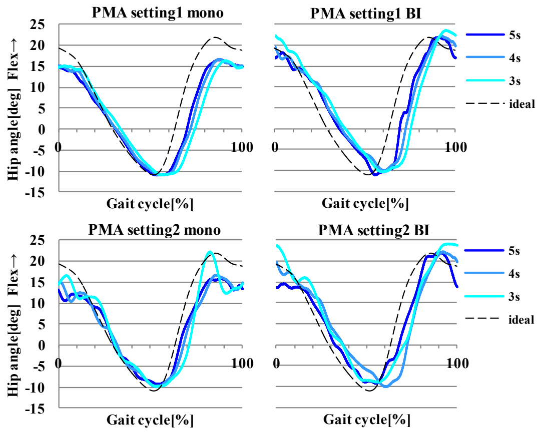


Figure 9: Hip joint angle.

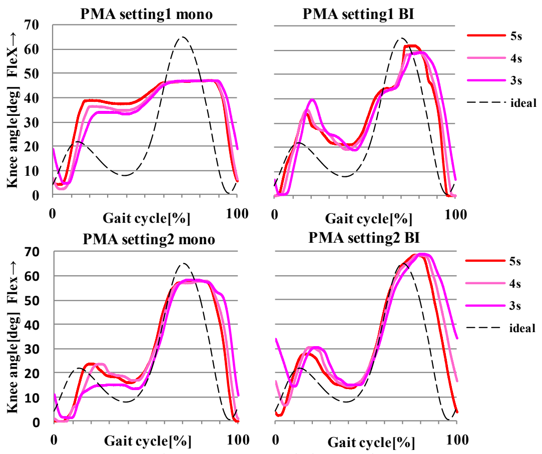


Figure 10: Knee joint angle.

VIII. CONCLUSION

In this paper, we determined the movements of the lower limb orthosis with the coordinates system and then constructed a control system which estimates antagonistic PAMs' length (contraction) from the hip and knee joint angles. Furthermore, we performed the controller tests for different gait cycles and PAM settings to see the performance of the lower extremity orthosis using the contraction model based controller. The results show that, the performance of the leg orthosis was satisfying. The system was able to achieve the maximum muscle moment at hip and knee joints, and was also able to perform the heel contact movement which could not be achieved by the use of mono-articular PAM actuators alone. This shows that the hip and knee joints' actuators worked effectively. However, if there is a load or subject on the orthosis system, the steady state error might occur within the system due to the nonlinearity behavior of the PAMs. The relationship between the contraction of a PAM and its pressure was measured without load. Thus, it is required to measure the PAM contraction's characteristics with load as there will be different test subjects and walking period (gait cycle). It is also necessary to consider the inertia effect and include the joints' moment measurement into the control system.

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