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A Lower Limb Exoskeleton with Hybrid Actuation

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Abstract— **In this paper, the lower limb exoskeleton uses a harmonic drive actuator and two pneumatic artificial muscles (PAMs). This hybrid actuation takes both advantages of harmonic drive and PAM. It provide high accuracy position control and compliant behavior. The disadvantages of each type of actuator are overcome. This exoskeleton is suitable for the strength augmentation of human lower limbs, such as the gait rehabilitation routine of hip and knee joints.**

I. INTRODUCTION

The exoskeletons are a class of device, designed to use as a clothing over the body, like a pants or a jacket, as is described for the term ”wearable robot”. This kind of robots serves as a tool to enhanced or replace partially the musculoskeletal system, due a some kinds of injuries as a neurological and neuromuscular diseases like hemopoietic or muscular dystrophy, muscle degeneration or due to old age. In the literature, we find that the first developments are focused in strength augmentation, mainly the military DARPA exoskeletons project. This developments have provided valuable information about the mechanical construction and electronic implementation theory. One of the most important of this developments is the BLEEX (Berkeley Lower Extremity Exoskeleton) [1]. Designed to enhanced the strength of the lower limb to help carry high loads driven by pneumatic actuator to powered the full legs (hip, knee and ankle joints). Other exoskeletons sponsored for the DARPA project are the Sarcos Exoskeleton [2] and the MIT Exoskeleton [3]. Many other projects non-military, proposed many other alternatives to enhanced the human capability. The latest version of [4], is an exoskeleton to powered the hip and knee joints directly with a DC motor coupled a Harmonic Drive gear, the robot are instrumented with EMG sensor to monitoring the muscular activity to actuate the joints. The development of two identically lower body exoskeletons with 10 DoF presented in [5], are driven by pneumatic muscles to actuated the hip, knee and ankle joints, one of them is for force augmentation and the other one for active assisted walking training.

Wearable robots are a class of metachromatic devices to increase human strength and resistance: They are useful to assist human limbs rehabilitation. The lower limb exoskeletons are the most common wearable robots, because human lower limbs are more susceptible to injuries due to the accidents, neuromuscular and neurological diseases, and muscular degeneration. The design object of this paper is to use the mechanical and electronic characteristics of human limbs as more as possible

It is estimated that between 7% and 10% of the world population has a kind of disability [6]. The population census of Mexico stated that in the year 2010 5.1% of the total population of the country have difficulty to walk or move, where 49% are men and 51% women. Some person have more than one disability, for example one person have motor and language problems with cerebral palsy. 39% disable people suffer from diseases, 23% disable people are due to old age, 16% is acquired by inheritance during pregnancy or at birth, 16% are due to accidents, and 8% people suffer for other reasons. Rehabilitation and increasing strength are possible methods to recover completely or partially for all of these causes

The traditional therapies are often focus on workouts on treadmills to improve an active or passive gait rehabilitation. The advantage of using a treadmill, it is easier to control the speed of the steps. Usually, the active trainer systems are based on exoskeleton robots, combined with a treadmill, for example: LokoHelp [7], ALEX [8], LOPES [9] and AutoAmbulator [10] and a compliant robotic orthosis for treadmill training [11]. The passive gait trainers are static robotic systems which allow guided movements of the limbs where the system powered the joint movements to achieve an optimal effect from the therapeutic and functional points of view. The goal of these systems is to obtain effective strengthening of muscles while developing joint mobility and movement coordination, see for example the Lambda [12] and Tsukuba [13] prototypes.

This paper deals with the design and modelling of an exoskeleton with four active DoF, for human lower limbs force amplification and rehabilitation. Our goal is provide an efficient tool for gait rehabilitation for the patient's legs and a force augmentation exoskeleton for old people and patients with muscular dystrophy, all in the same device. Furthermore, the exoskeleton length can be adapted to fit with the size of lower limbs from the Mexican population considering its anthropometry factors.

II. LOWER LIMB EXOSKELETON

We propose a pseudo anthropomorphic architecture with four active Degrees Of Freedom (DoF). The exoskeleton powers the active flexion/extension DoFs for the hip and knee joints via a hybrid pneumatic-electric system composed for a harmonic drive actuator placed directly on the joints

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and coupled with a transmission based on Bowden cables in an antagonistic configuration of two pneumatic muscles. The ankle flexion/extension DoF is passive. The hip joint has 3 DoF; the abduction/adduction and internal/external rotation are passive and the flexion/extension is active. The knee has a passive DoF for abduction/adduction movement. The structure of the exoskeleton mainly will be constructed

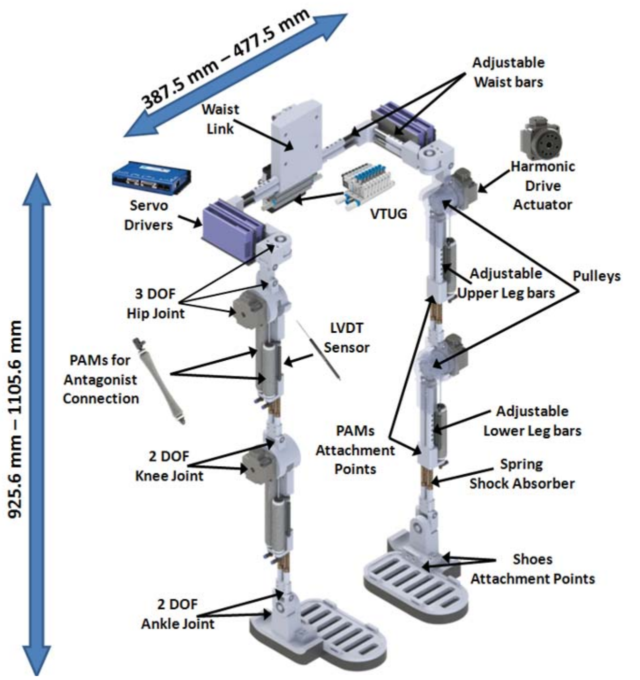


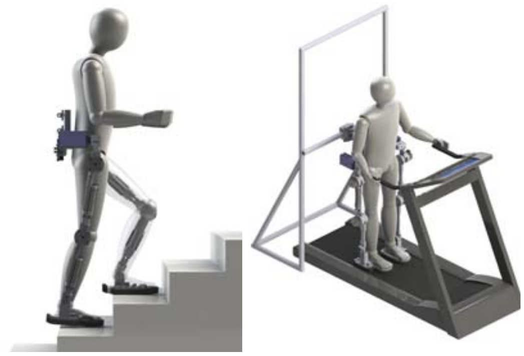
Fig. 1: The 3D CAD representation of the exoskeleton, with principal components and fully assembled.

from nylamid for the joints sections and machined using a CNC machine and the adjustable elements for the exoskeleton links from aluminium bars and tubes. The adjustable elements for the upper and lower leg incorporate a spring shock absorber, to reduce the collision effect in the limbs of the operator. This elements can be adjusted easily and quickly as needed, and can change its length up to 100mm. See Fig.1.

The exoskeleton is designed to work as a strength augmentation exoskeleton as shown in Fig.2a and also as a exoskeleton for active gait rehabilitation using a treadmill, in Fig.2b. Many commercial devices do not allow configuration changes to be used in other activities, this reduces to exploit their capabilities. Therefore our proposal allows changing from one activity to another without making major changes. For this goal, we designed the waist link able to easily connect with a fixed structure to work together a treadmill to perform as a gait trainer as shown in figure, in same way this element can be connected with a bag that include a battery and air supply to work as a augmentation exoskeleton.

A. Anthropometry factors

The measurements and proportions of the human body are very important, since it allows us to identify the differences



(a) (b)

Fig. 2: Configuration of the exoskeleton for multiple purposes, in (a) the exoskeleton is used for augmentation force purposes, and in (b) is used for active gait rehabilitation using a treadmill.

between individuals, groups, races, etc. Consider the anthropometric studies to the target population is very important when developing an exoskeleton. For this reason we consider the measurements of the Mexican population reported in [14], this study include the size of the male and female population between 18 and 65 year old, as shown in the Table II. Now with this information together the standardized proportions of the human body reported in [15] (see Fig.3), we design the links of the exoskeleton with the ability to change its length to adjust for measures of the upper leg, lower leg and the waist limbs from the target population.

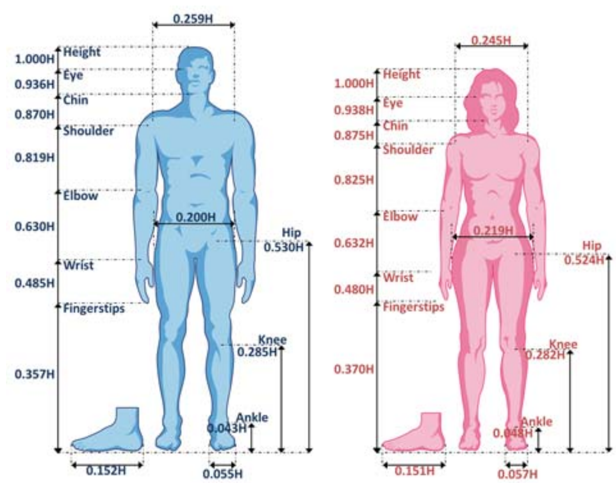


Fig. 3: Standardized proportions of the male and female body, as a function of its height [15].

Another important anthropometry factor is the range of motion of the human joints. Analyzing movements, we note that most of the time we don't care the maximum range of the joint, but the values of comfort angles with various joints, out of which the work to be performed is difficult painful or even dangerous for people. Note that the clevis fitting comfort angles also depend on the age, physical training, the anatomical and functional differences, etc. We consider the comfort angles [16], to fixed the range of the exoskeleton joints, mechanical stop is proposed to ensure safety for the limb's operator. The comfort angles are given in the Table I.

TABLE I: Comfort angles for the lower limb joints, considered for the exoskeleton's joints design.

Joint	Movement	Range
Hip	Hyperextension	0 - 45°
	Flexion	0 - 130°
Knee	Flexion	0 - 135°
Ankle	Dorsiflexion	0 - 20°
	Plantarflexion	0 - 40°

TABLE II: Size of Mexican population for industrial workers between 18 and 65 year old. The study was realized with a total sample of 600 subjects, with 204 females and 396 males [14].

Dimensions	Men			Female		
	Percentile			Percentile		
	5	50	95	5	50	95
Height (mm)	1576	1668	1780	1471	1570	1658
Weight (Kg)	55.31	72.10	97.3	48.0	60.5	80.0
Waist diamter (mm)	310	341	387	321	359	420
Hip height (mm)	810	872	940	759	826	896
Knee height (mm)	434	476	526	411	446	491
Foot lenght (mm)	242	262	282	217	235	255
Foot width (mm)	88	98	108	81	88	97

B. Hybrid actuator

We proposed a hybrid pneumatic-electric system to powered the exoskeleton joints. The aim to combine two class of power supply, is to provide the device the advantages of each class of actuator. On the one hand the harmonic drive actuator has a high torque, high accuracy position and relatively small dimensions, this characteristic are ideal for gait rehabilitation where the repetitive factor in the gait cycle, is very important to facilitate and accelerate the rehabilitation and the recovery of weak and injure people. In other hand the pneumatic muscle actuators (PAMs) are lightweight and have high power/weight and power/volume ratios as compared to all the existing actuators and also has intrinsic elasticity (compliance) which can be used in providing compliant actuation, specially when the device is also led to people with involuntary muscle contractions due a neurological disorder or other causes. Then, with this characteristic we proposed a hybrid actuator to provide a high accuracy position and compliant actuation for the exoskeleton's joints. A revolute joint is design for hip and knee sagittal plane motions, as shown in Fig.4. First a Harmonic Drive actuator is mounted over a nylamid machined piece, with mechanical stops to limit the range of motion on base of Table I. A double groove pulley is employed to construct a transmission based on Bowden cables actuated by two PAMs, the Bowden cables are fixed at the top of each muscle, and these are fixed in the bottom at the end of the adjustable exoskeleton's link. Both mechanisms are coupled through six holding screws, to fix the pulley to the Harmonic Drive's axis.

The pneumatic setup is implemented like is explained in [17]. The PAMs are driven by an array of electrovalent grouped in a valve terminal fixed at the waist link, each muscle includes a LVDT linear motion sensor for position sensing and a pressure sensor. The muscles have a diameter of 30mm, with a contracted length of 210mm and a maximum length of 290mm fully extended [18].

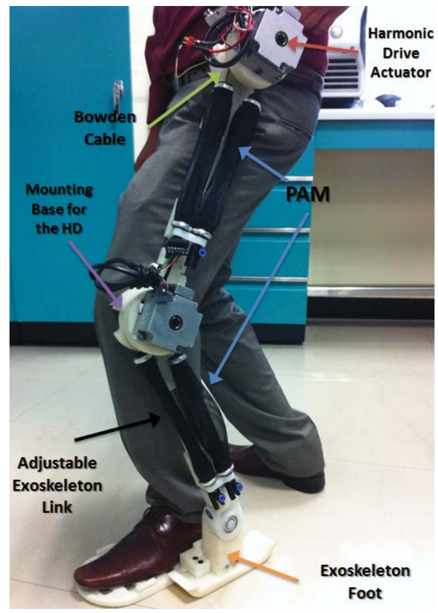


Fig. 4: Current construction of the Exoskeleton and joint components.

C. Wearable motion sensor

The system design concept is show in Fig.5. The goal is use the wearable motion sensor as a tool to capture the movement of the lower limbs from the different test subjects and generate a base of gait patterns to be used a simulation level for design control laws for the prototype and also to develop an exoskeleton controlled by electromyography signals. The electromyography signals are recorded over the low limb. The measured muscles are the vasts laterals muscle and gastrocnemius muscle (for each leg) as shown in the Fig.5, for measuring the hip and knee joints movements. The corresponding electromyography signals are amplified and filtered accordingly to obtain an estimate of the angular position and angular velocity in the sagittal plane for each joint. The goal is use this kind of pattern activation from muscle fibers to predict the intend of the operator to move his leg, and then the exoskeleton can detect these signals and so begin moving to match the movements of the operator's leg. The electromyography signals will be transmitted by a wireless connection, which is intended increase efficiency of the exoskeleton allowing harmonic movements that enhanced the rehabilitation process.

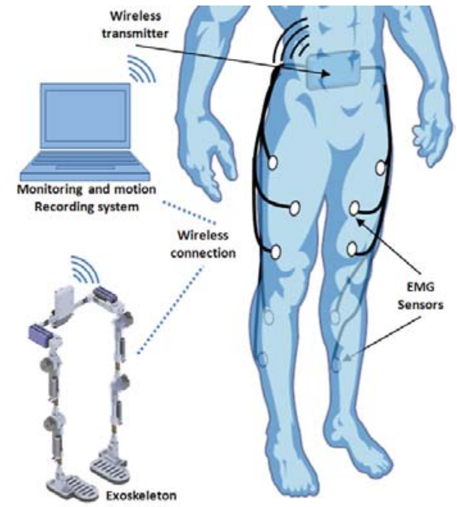
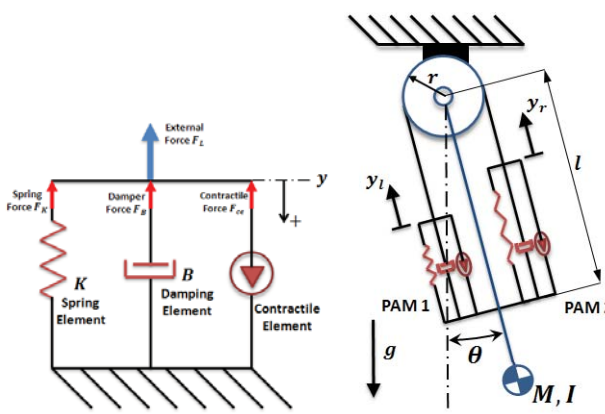


Fig. 5: Wearable motion sensor concept, using EMG sensors and wireless connection for signals monitoring and exoskeleton control.

III. Mathematical modelling

A. Pneumatic Muscle Actuator

The pneumatic muscle actuator is very similar in action to a human muscle. The muscle can be studied with a three-elements phenomenological model, which is a parallel arrangement of a contractile element, damping element and spring element as shown in Fig.6a. The coefficients of each element can be expressed as a function of the pressure P [19], then defined y as position variable for muscle displacement, the equation of motion is given by



(a) (b)

Fig. 6: In (a) is presented the Three-element phenomenological model for the PAM, in (b) Antagonistic PAMs configuration and parameters conventions for the pendulum model. The muscles act as a three-element mechanism with its parameters as a function of the internal pressure.

$$M\ddot{y} + B(P)\dot{y} + K(P)y = F_{ce}(P) - F_L \tag{1}$$

where $K(P)$ is the spring coefficient, B(P) is the damping coefficient, this coefficient has two parts, $B_c(P)$ for PAM contraction and $B_r(P)$ for PAM relaxation, $F_{ce}(P)$ is the effective force of the contractile element, the external force F_L in the Fig.6a is due to the external load plus the inertial load $M\ddot{y}$. The coefficients are given as follows

$$\begin{aligned} K(P) &= 5.71 + 0.0307P \\ B_c(P) &= 1.01 + 0.00691P \\ B_r(P) &= 0.6 - 0.000803P \\ F_{ce}(P) &= 179.2 + 1.39P \end{aligned}$$

The coefficients holds for pressure P in the range of $30 \leq P \leq 90$ psi ($2 \leq P \leq 6$ bars). Then the total force produce by the pneumatic muscle is defined as

$$F_{muscle} = F_{ce}(P) - B(P)\dot{y} - K(P)y \tag{2}$$

In other hand, the connection of two muscles around a double groove pulley of radius r, for antagonist configuration as in Fig.6b, with the connection line rigidly attached to the pulley to prevent slipping. The pendulum equation of motion due the antagonist connection is given as follows

$$I\ddot{\theta} + B\dot{\theta} + mglsin(\theta) = \tau_{muscle} \tag{3}$$

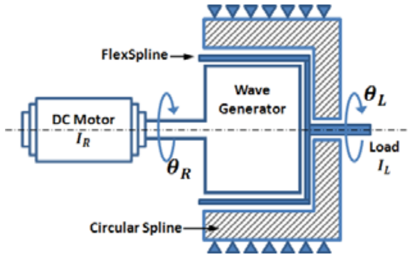
where, I is the pendulum inertial around the joint, m is the pendulum mass, g is the constant gravitational acceleration, l is the pendulum length and T_{muscle} is the torque generated by the muscles, given by

$$\begin{aligned} \tau_{muscle} &= \tau_l - \tau_r \\ &= (F_l - F_r)r \end{aligned}$$

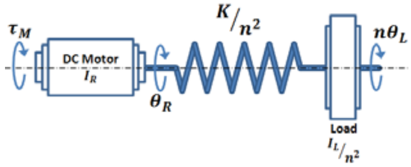
whit F_l and F_r given in (2) and r is the radius of the pulley.

B. Harmonic Drive Actuator

The mechanism Harmonic Drive, is a power transmission system capable of developing high ratios, giving the set a high accuracy of positioning, with a weight/volume ratio low. Composed by a wave generator, from rigid steel core having an elliptical shape with very small eccentricity. It is surrounded by a flexible race ball bearing. The flexible spline (or flexible) is a thin-walled hollow cup made up of alloy steel. External gear teeth are machined at the open end of this cup and the closed end is connected to the output shaft, Fig.7a. The exoskeleton has four active DoF, each has a built-in Harmonic Drive actuator for the directly joint actuation, we used the model FHA-14C-100-US200-E [20], with an absolute encoder resolution of $800,000$ p/rev, with a gear ratio reduction of $100 : 1$ and 24VDC motor, all in one little package. The exoskeleton joint driven by an Harmonic Drive actuator can be see as a motion transmitter element containing an internal elasticity of constant K, as represented in Fig.7b. The equation (4) describes the dynamic of actuator [21]



(a)



(b)

Fig. 7: In (a) is presented the mechanism Harmonic Drive, showing the principal elements, the wave generator, the flexspline and the circular spline, in (b) is shown the equivalent mechanism, used to model the joint of the exoskeleton driven by an Harmonic Drive actuator.

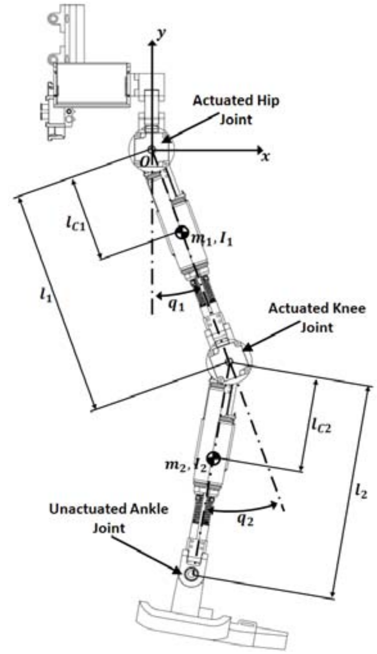


Fig. 8: The exoskeleton can be modelled as a double pendulum in the sagittal plane.

$$I_R\ddot{\theta}_R + \frac{K}{n^2}(\theta_R - n\theta_L) = T_{HD} \tag{4}$$

$$I_L\ddot{\theta}_L - K(\frac{\theta_R}{n} - \theta_L) = 0 \tag{5}$$

$$T_{HD} = T_m - T_{at}$$

where I_r is the rotor inertia (Kgm^2), I_L the load inertia (Kgm^2), K is the elasticity constant for the motion transmitter element (Nm/rad), n the gear ratio, T_{at} the friction torque, T_m the motor torque (Nm), θ_R the rotor angular position (rad) and θ_L the load angular position (rad). The torque T_{HD} is the torque effectively applied to the load, the friction can be modelled as a function of the angular velocity and position, and the friction torque can be estimated as shown in [22], [21].

C. Dynamic model of the lower limb exoskeleton

The major rotation for the hip and knee joints during gait cycle occurs in the sagittal plane, as is reported in [23]. As can be see in Fig.1, the exoskeleton hip and knee joints are only actuated over the sagittal plane, the ankle joint was not actuated. Each exoskeleton's legs were modelled using Euler-Lagrange formulation, according to parameters conventions for the double pendulum model as shown in Fig.8. The dynamics of the human's leg and the exoskeleton's leg are given by

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau_{total} \tag{6}$$

where the input $\tau_{total} = [\tau_{exo_{hip}}; \tau_{exo_{knee}}]$, these inputs are a function of the combination of the par generated by pneumatic muscles and the par generated by the harmonic drive actuator

$$\tau_{exo_{hip}} = f(\tau_{HD_{hip}}, \tau_{muscle_{hip}}) \tag{7}$$

$$\tau_{exo_{knee}} = f(\tau_{HD_{knee}}, \tau_{muscle_{knee}}) \tag{8}$$

Is worth to mention, that one of most important goals for us, is design a controller to couple efficiently these dynamics and obtain the best performance of the exoskeleton.

D. Preliminary results

We focused first in the pneumatic part, to obtained the numerical results from the dynamic of the exoskeleton's leg given in (6), through the closed loop joint control scheme shown in Fig.9. First a PD controller is used for tracking trajectory, to generated a desired Torque τ_d, then a PID controller is used to control the PAM's dynamic given in (1), to obtain the Torque τ_s through the antagonist pair of PAM's. We proposed two desired trajectories for the Hip and Knee joints, θ_{d-Hip} and θ_{d-Knee} respectively, generated by the following functions:

$$\theta_{d-Hip} = A_1(1 - e^{-0.02t^2} + C_{i_1}) + C_1(1 - e^{-2t^3})\sin(\omega_1 t)$$

$$\theta_{d-Knee} = A_2(1 - e^{-0.02t^2} + C_{i_2}) + C_2(1 - e^{-2t^2})\sin(\omega_2 t)$$

The values are $A_1 = (B_1 - C_{i_1})$, $B_1 = \frac{40\pi}{180}$, $C_1 = \frac{45\pi}{180}$, $B_2 = \frac{-5\pi}{180}$, $C_2 = \frac{30\pi}{180}$ and $\omega_1 = \omega_2 = \frac{2\pi}{15}$. The value of the constant ω_1 and ω_1 were selected to perform four repetitions per minute. Fig.10 shows the results of the tracking trajectory for the two joints with the previously consideration. It was observed that the dynamic of exoskeleton's leg converges quickly to the desired values.

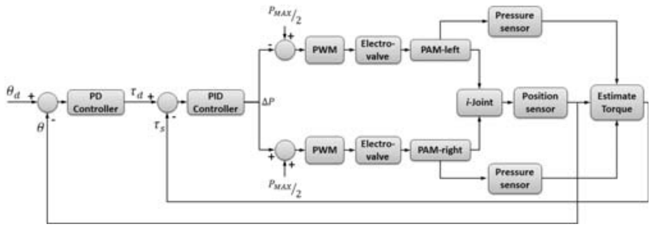


Fig. 9: Joint control scheme

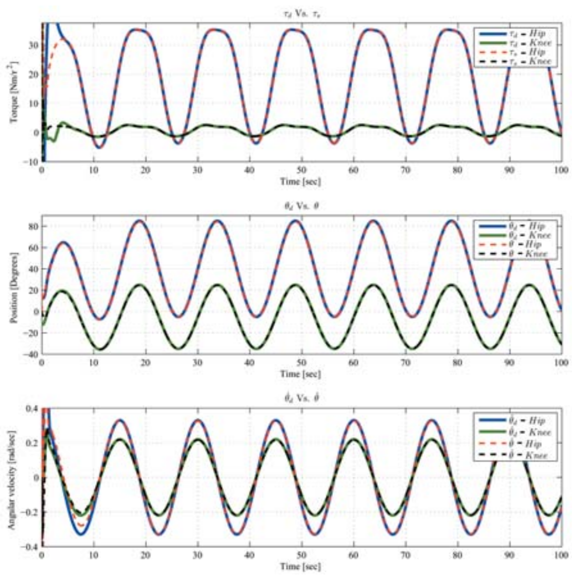


Fig. 10: Numerical tracking trajectory results for the exoskeleton's leg

IV. Conclusions

In this paper, we proposed a novel design of lower limb exoskeleton for multiple purposes. We combine two different type of actuators to take both advantages. The high air pressure of PAM generates enormous force. Since PAMs in the antagonist setup provide compliant control, they are ideal for the force augmentation part in the exoskeleton. The position accuracy of the harmonic drive actuators are high, and dimensions are relatively small. These properties satisfy the requirements of the cyclical rehabilitation routines. The prototype is still under the fabrication. We will use it to test different rehabilitation jobs with the wearable motion sensor.

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