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Design and Simulation of Leg-Exoskeleton Suit for Rehabilitation

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Abstract - In everyday activities, the injuries to lower limb are considered to rehabilitate in urgent priority. The rehabilitation is to restore the patient's physical, sensory, and mental capabilities due to injury, illness, or disease in normal condition. The typical habilitation for lower limb is separated in three types , which ar e active , passiv e and active -assi stive mode. Active mode is one important aspect of rehabilitat ion for increasing or maintaining joint function providing appropriate resistance to the muscles to increase endurance and strength . For passive mode , patients cannot activ ely participate in rehabilitation and no effort is required from them. Patient's lower limb will be driven by exoskeleton suit. This rehabilitation motion is influenced by bone surfaces within the joint, joint capsule, ligaments, tendons, and muscles acting on the joint. In this paper, the new hardware design is introduced and the possible motions of each joint are simulated. The relative positions of each joint are determined by Denavit- Hartenberg method. In simulation the revolute, speed and acceleration of each joint in left side are studied to construct the real hardware.

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Strictly as per the compliance and regulations of:

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I. Introduction

Injuries to lower limb joints, especially the knee and ankle are most of all musculoskeletal disorders. Because of the importance of the lower limb in everyday activities such as walking, running, the injury to these joints is urgently considered in practice. An exoskeleton suit is a powered mobile machine supplied at least part of the activation-energy for joint movement. The suit may be designed to assist and protect human to aid the survival in other dangerous environments. One of the main purposes uses an exoskeleton suit to enable a soldier to carry heavy weight during running or climbing including armor or weapon. Most of exoskeleton suit is designed by using hydraulic system. Another application could be therapy habilitation, nursing in particular. An exoskeleton suit could reduce therapy process for patient to be trained by one therapist.

Takehito et al. [1] described force-feedback mechanism of the rehabilitation system for upper limbs with active and passive mode. Steven K. Charles et al. [2] purposed a test bed to study the potential of using robots to assist in and quantify the neuro-rehabilitation of motor function. Their work focused on wrist rehabilitation, which provides three rotation degrees of freedom. Ming-Shaung Ju et al. [3] designed a robot system to assist for rehabilitation of patients with neuromuscular disorders by performing various movements. Their controller was stable in limited range of movement and force. Ahathe Koller-Hodac et al. [4] purposed a new way to assist patella mobilization during knee rehabilitation programs. They use the robotic device to perform exercises on regular basic during therapy process. S.Slavic et al. [5] developed the concept of mobile gait rehabilitation system and presented the simulation results to demonstrate the translation degrees of freedom between support platform and exoskeleton device. Robort Riener et al. [6] purposed new human-centered robotic for rehabilitation of gait in patients with movement disorders. Pengju Sui et al. [7] presented device for the ankle rehabilitation and types of motion and analyzed kinematics and workspace. Tobias Nef and Robert Riener [8] explained the principle of exoskeleton for shoulder movement providing motion of the center of joint. The current research of exoskeleton suit from Pin Wang and K.H. Low [9] developed a natural and tunable rehabilitation gait system to assist the gait rehabilitation with body weight support. Mohamed Bouri et al. [10] developed the device introducing a stationary rehabilitation system. Their work presented the flexibility and diversity of use for diagnosis. Qingling Li et al. [11] presented wearable rehabilitation robot for hemiplegic patients.

II. Leg-Exoskeleton Suit System Design

The system of leg-exoskeleton suit is properly designed to hold with human leg by belts integrated with DC motors with encoder and force sensors, microcontroller and drive system. At shaft of DC motor at each joint of the leg-exoskeleton suit, encoders are integrated to measure the rotational angle of hip, knee and ankle joints. In design, the leg-exoskeleton suit has six degree of freedom. Each leg has three DOFs for hip, knee and ankle as shown in figure 1. The weight of the leg exoskeleton suit is very important. The structure is not only light but also ensured for its durability. Thus, aluminum alloy is selected to be the structure of

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the leg exoskeleton suit. The array of force sensors are attached under belts at foot area, near under knee joint and under hip joint to measure force exerted by the human that use as input in active mode. The hardware of leg exoskeleton suit is driven by six motors mounted with encoders. The motor drive system, encoders and sensors are exchange information with microcontroller.

Then microcontroller will send the information to PCstation to display the information of leg-exoskeleton suit and sensors. The PC-station can receive the command from user with GUI application.

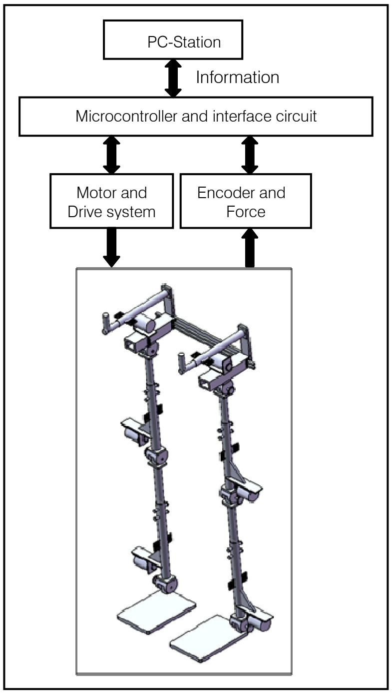

Figure 1 : The exoskeleton suit model.

III. Analysis for Leg-Exoskeleton Suit

The force analysis of mechanism is firstly considered to design the leg-exoskeleton suit. For the hip joint, torque generated by motor $(M_{1,4})$ must be more than torque generated by total weight of leg exoskeleton suit plus human leg.

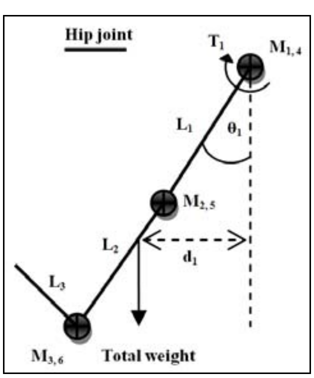

Figure 2 : Forces act at hip joint.

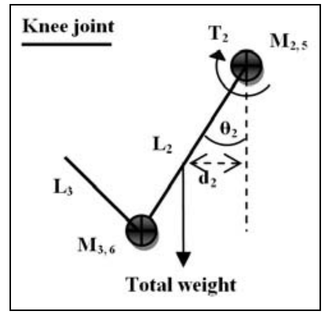

Figure 3 : Forces act at knee joint.

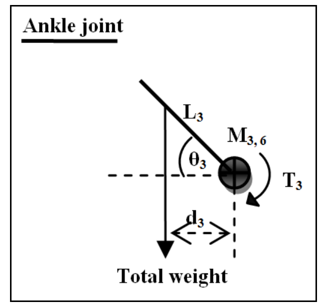

Figure 4 : Forces act at ankle joint.

For the knee joint, torque generated by motor $(M_{2,5})$ must be more than weight from knee joint to link 3.

Also, the torque by motor $(M_{3,6})$ can lift the ankle in desired position. The torque and total weight can be given as equation 1.

$$T_{hip/knee/ankle} = W_{hip/knee/ankle} \cdot d_{hip/knee/ankle} \quad (1)$$

which

$T_{hip/knee/ankle}$ = Total torque generated by motor at hip, knee and ankle joints

$W_{hip/knee/ankle}$ = Total weight of hip, knee and ankle

$d_{hip/knee/ankle}$ = The length from hip, knee and ankle joints to centre of mass due to vertica line

To calculate position of hip, knee and ankle, the Denavit-Hartenberg method is used. From the figure 5 the parameter for Denavit-Hartenberg equation must be specified due to reference coordinate.

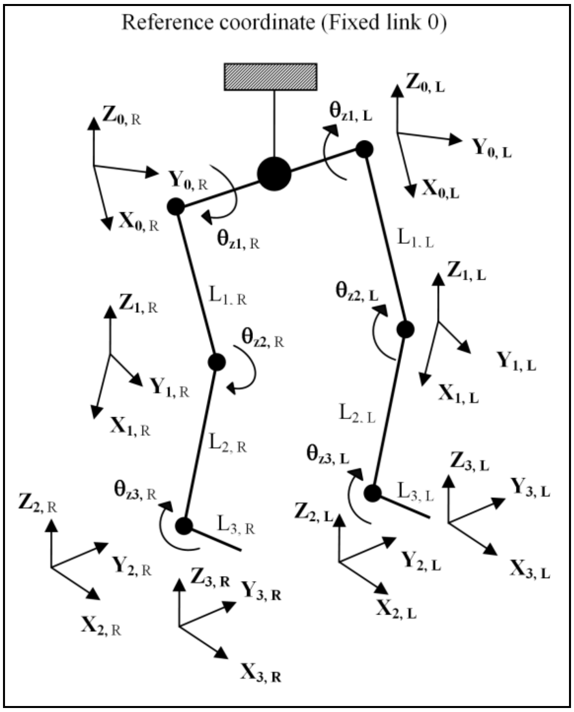

Figure 5 : Coordinates of leg-exoskeleton suit.

All parameters of left leg-exoskeleton suit are given shown in table 1.

Table 1 : Parameters of left leg for Denavit-Hartenberg equation.

Left link	$\theta_{i,L}$	α_i	a_i	d_i
1	$\theta_{1,L}$	0	$L_{1,L}$	0
2	$\theta_{2,L}$	0	$L_{2,L}$	0
3	$\theta_{3,L}$	0	$L_{3,L}$	0

For the right leg-exoskeleton suit, the parameters are given in table 2

Table 2 : Parameters of right leg for Denavit-Hartenberg Equation.

Right link	$\theta_{i,R}$	α_i	a_i	d_i
1	$\theta_{1,R}$	0	$L_{1,R}$	0
2	$\theta_{2,R}$	0	$L_{2,R}$	0
3	$\theta_{3,R}$	0	$L_{3,R}$	0

From general equation of transformation matrix from coordinate i-1 to coordinate i can be given below (McKerrow [12]).

$$^{i-1}_{\;\;i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The parameters of left leg-exoskeleton can be substituted in coordinate transformation matrix. For left hip joint, the transformation matrix with $i = 1$is given.

$$^{0}_{1}T_L = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & L_{1,L}\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & L_{1,L}\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformation matrix for left knee joint with $i = 2$ is Given

$$^{1}_{2}T_L = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_{2,L}\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & L_{2,L}\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

And the transformation matrix with $i = 3$ for left ankle joint is given.

$$^{2}_{3}T_L = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & L_{3,L}\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & L_{3,L}\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

As same consideration of the left leg-exoskeleton suit, the coordinate transformation matrixes of right legexoskeleton suit are given.

$$^{0}_{1}T_R = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & L_{1,R}\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & L_{1,R}\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{1}_{2}T_R = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_{2,R}\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & L_{2,R}\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{2}_{3}T_R = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & L_{3,R}\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & L_{3,R}\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

To control position by left or right motors at hip joints (M_1 or M_4) due to reference coordinate, the transformation matrixes can be directly calculated by $^{0}_{1}T_{R,L}$. Then the transformation matrixes by left or right motors at knee joints (M_2 or M_5) due to reference coordinate can be calculated.

$$ {}^{0}_{2}T_{R,L} = {}^{0}_{1}T_{R,L} \cdot {}^{1}_{2}T_{R,L} \quad (2) $$

And the transformation matrixes due to reference coordinate by left or right motors ($M_{3,6}$) can be calculated.

$$ {}^{0}_{3}T_{R,L} = {}^{0}_{1}T_{R,L} \cdot {}^{1}_{2}T_{R,L} \cdot {}^{2}_{3}T_{R,L} \quad (3) $$

IV. Control Algorithm for Leg - Exoskeleton Suit

The principle of physical rehabilitation involves exercising and manipulating the body. It can restore joint and muscle function such as helping for people stand, body balance, walk, and climb stairs better. There are main three types of physical rehabilitation, which are active, active-assistive and passive motion. In order to leg-exoskeleton suit can operate following all types of rehabilitations, the control algorithm should be designed to cover all operations. In this work six DC motors are mainly used to drive leg-exoskeleton suit at hip, knee and ankle joints. In design of control algorithm the DC motor model is firstly considered. To control DC motor in desired position, the model of DC motor must be considered.

From mechanical torque applied to motor shaft, it equals torque constant K_T multiply by electrical armature current I_a.

$$ T_{motor} = K_T \cdot I_a \quad (4) $$

And the applied torque generates angular velocity **ω** according to the inertia ***J*** and friction ***B*** of motor with load.

$$ T_{motor} = J \cdot \dot{\omega} + B \cdot \omega \quad (5) $$

From equation 4 and 5, the acceleration can be given as

$$ \dot{\omega} = \frac{T_{motor}}{J} + \frac{B}{J} \cdot \omega \quad (6) $$

And the equivalent block diagram can be shown in figure 6.

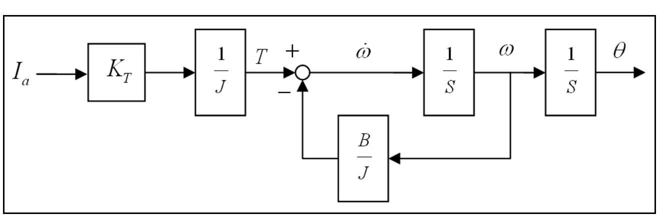

Figure 6 : DC motor block diagram.

For active motion, patients can exercise muscle or joint by themselves. In this mode the patients can move their hip, knee and ankle joints in desired position.

In order to the leg-exoskeleton suit can sense patient's force, the rows of force sensor are attached under belts at link 3 (L_3), link 2 (L_2) and link 1 (L_1).

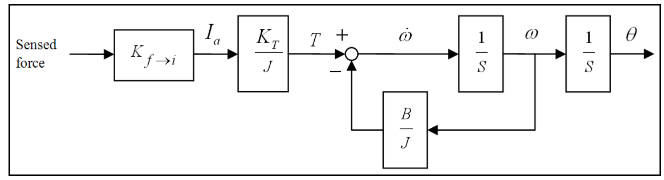

Figure 7 : Block diagram of active mode for rehabilitation.

When patient move left or right joint at hip, knee or ankle, the sensor will detect level of force and send the data to the central control unit (CCU). Then the CCU will execute and send the correspondence information to motor drive system. The resultant vector of sensed force at each joint both sides is used to adjust the current by gain $K_{f \to i}$, which will send the position as output shown in figure 7. In the passive motion mode, patients cannot actively participate in rehabilitation. Patient legs will be driven by exoskeleton suit. No effort is required from them. The desired positions of each joint must be firstly specified. In this mode, the CCU will execute the desired position as input and then sent information to motor drive system. To keep the precision in position control, the encoders are used for measuring the angle of all joints as position feedback in closed loop by using classical PID control.

$$ \delta\theta = \theta_d - \theta_a \quad (7) $$

The different angle between desired and actual angle is fed to PID loop.

$$ u = k_p \cdot (\delta\theta) + k_i \cdot \int (\delta\theta) \cdot dt + k_d \cdot \frac{d(\delta\theta)}{dt} \quad (8) $$

Where,

θ_d is the desired angle,

θ_a is the actual angle,

$\delta\theta$ is the difference between desired and actual angle,

k_p, k_i, k_d are gain parameters of PID.

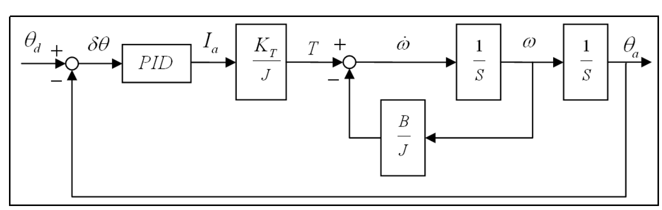

Figure 8 : Block diagram of passive mode for rehabilitation.

For the last active-assistive mode, this mode is the combination of active and passive motion for patients who can move their muscles with a little help or who can move their joints but feel pain when they do. The active-assistive mode is used when patients has capability to move their joints but has not reached the desired level. For this mode, the patients will move joints actively at start with active motion. When the patients cannot move their joints and need help, the passive motion can be suddenly activated by patients and then the joints will be continue driven by leg-exoskeleton suit to desired point. From the block diagram, when patients start with active motion to move any joint, the information of sensed force will be sent to motor drive system.

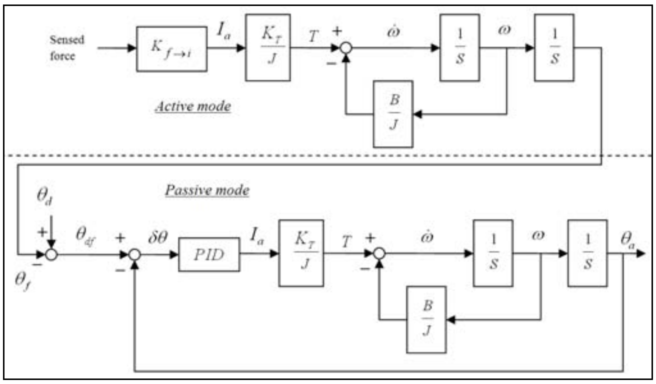

Figure 9 : Block diagram of active-assistive mode for rehabilitation.

The output θ_f from active mode will be compared with desired position θ_d . If position from active mode θ_f cannot reach to desired position θ_d , the different position θ_{df} is sent to passive mode and then the joints will be driven by leg-exoskeleton suit until its positions reach to desired position.

V. Simulation and Results

The kinematic motion of leg-exoskeleton suit is analyzed and simulated by MATLAB software. Firstly, we designed the structure of leg-exoskeleton suit by using robotic toolbox release 7.1 by Corke[13]as shown in figure 10. The hardware consists of main three joints in left and right sides and the parameters relationship between the links and joints is described based on Denavit and Hartenberg method. In simulation, the revolute, speed and acceleration of joints are studied how is the possible motion of the leg-exoskeleton suit. The results of simulation are considered to design and construct the real hardware. Many types of motion are simulated to test the conflict of links and joints. The angles of left hip, knee and ankle joints are specified in simulator with started position (0, 0, 0) and the final angle of joints are position (-90°, 45°, 90°) in 10 second. The revolute angle, velocity and acceleration of hip, knee and ankle joints are shown in figure 11-13 respectively.

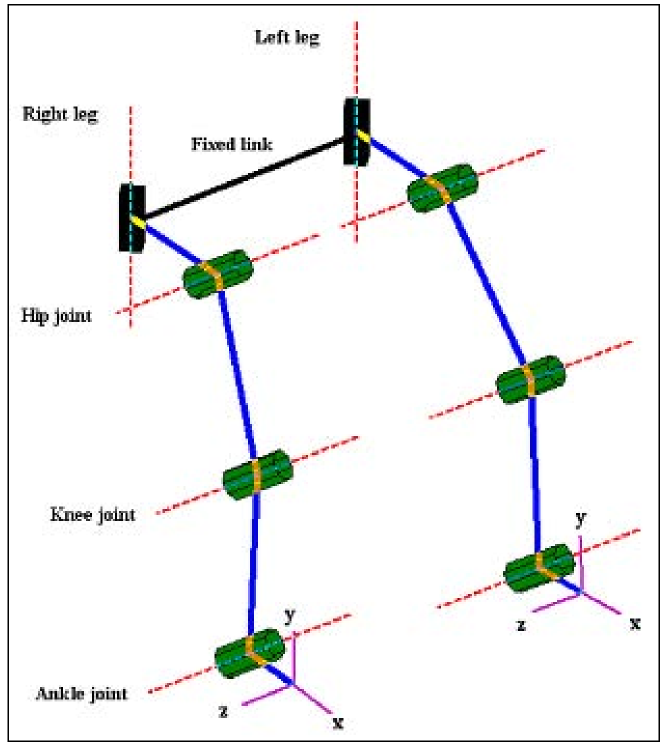

Figure 10 : The structure of leg-exoskeleton suit is designed by robotic toolbox.

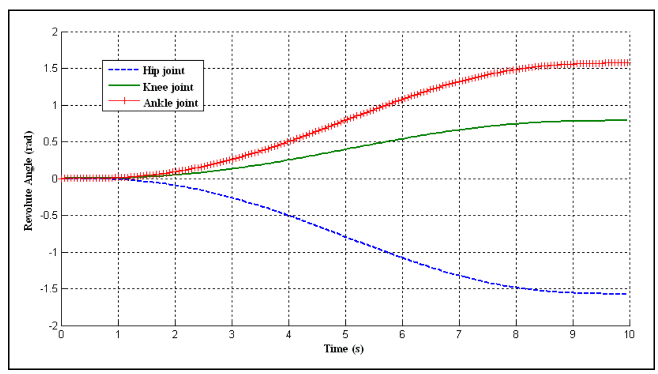

Figure 11: The revolute angle of hip, knee and ankle joints.

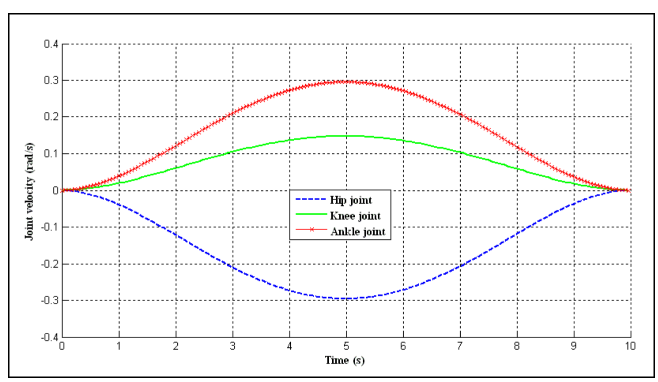

Figure 12 : The velocity of hip, knee and ankle joints.

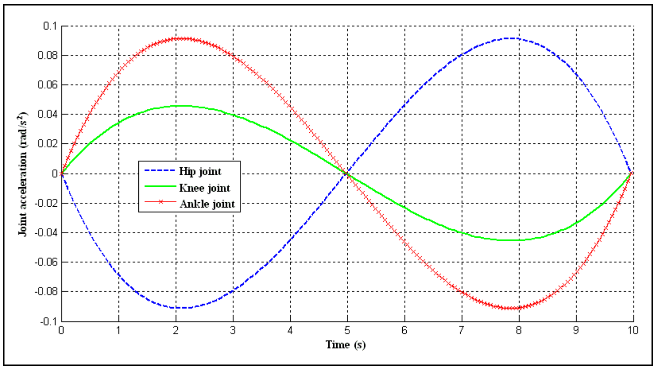

Figure 13 : The acceleration of hip, knee and ankle joints.

VI. Conclusions

The study of possible motion of leg-exoskeleton suit is focused to construct the real hardware. The design of leg-exoskeleton suit is achieved by Solid work software. By this software, the possible motion and conflict between links and joints can be simulated. In this work, three types of physical rehabilitation, which are active, active-assistive and passive motion, are analyzed and simulated. In order to leg-exoskeleton suit can operate following all types of rehabilitations, the control algorithm is designed to cover all types. In simulation, the active motion is only accomplished. The sensed force is used as input in control algorithm and the output as revolute angle, velocity and acceleration of hip, knee and ankle joints is given. The revolute, velocity and acceleration of each joint in left leg are simulated by MATLAB robotic toolbox. The leg-exoskeleton suit is specified at position of hip, knee and ankle joint angle (0, 0, 0) and the end of trajectory is position (-90°, 45°, 90°).

VII. Acknowledgement

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