INVESTIGATION OF BIPEDAL HUMAN GAIT DYNAMICS AND KNEE MOTION CONTROL

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ABSTRACT

Walking is one of the principal and complex movements of the human body. The human locomotion with two legs is a periodic physical activity occurring by driving of the bones by muscles, which are stimulated by electrical signals transferred by neurons from the brain.
In this paper a kinematical analysis is firstly made using a simple mathematical model and mechanical equations, which describe the physical events, that cause normal walking procedure. Lagrange’s method and equations are used for the kinematical solution of motion.

After this theoretical application, in contrary to many previous, generally model based mathematical studies; real measurements of both hip and knee angles of a healthy human being during bipedal walking under various circumstances are registered to make a certain decision of normal walking conditions. Using a special designed prophase, equipped with angle position measuring potentiometers, a series of experiments are made. For these experiments, data values of four different people are measured and captured by computer and a statistical evaluation is done to find out the average values, which can be taken in consideration as significant characteristics of normal walking.

Thus instead of very complex, time consuming model based studies with their insufficient accuracy, a real time and application oriented approach has been the main purpose of this study.

After exposing the relative motions of hip and knee angles, a computer-based control of the knee motion of an amputee without lower link (tibia) in accordance to the motion of femur through hip joint is investigated. The second and main goal of this study is then to design an optimal prosthesis for the amputee under these considerations.

Various measurements and tests like surface walking, walking on slopping surface and staircase walking are made to investigate the real parameter variations. In this way it is considered to reach a reality true theoretical modeling of the human walking dynamics

KEYWORDS: femur, tibia, control, joint, computer, amputee, interface

1. INTRODUCTION

1.1. What is Principal Meaning of Walking?

Walking is one of the principal movements of the human body. It is a procedure that is done by the consequent steps. The pendulum movement of leg around pelvis, which is made between the time that foot leaves the contacted surface and touches again, is called step. During this pendulum motion the other leg is contacted to the surface and carries all the load of bodyweight. When the dynamic leg passes the static leg the body tends to fall forward but the heels of the moving leg touches the surface so the body automatically prevents falling. During that sequence reversed swinging arms with the legs help the body to gain its balance. This is the simplest explanation of a walking period. All other types of walking (e.g. fast walking, running , climbing ...) are related to how much you repeat this period , how fast you are doing it and which in which angle you are with 0 radian.

1.2.What is Anatomical Meaning of Walking?

Walking is one of an everyday task that we do and we do not think about how it occurs anatomically. In truth these tasks require a sophisticated sequence of activities that is impressive. The nervous system provides the pathways to permit us to carry out such precise activities. To understand how it is able to exert such exacting control on our bodies , we have to examine neurons , the most basic part of the nervous system , and by considering the way in which nerve impulses are transmitted throughout the brain and the body.

If we consider walking as a swift working mechanism, brain is the control system (regulator) of the machine and neurons are the electrical wires that brain get and send messages. These messages are purely electrical and neurons follow an all-or-none law. They are either on or off; once triggered beyond a certain point , they will fire. Messages from brain reaches to muscles with the help of these electrical wires.

Exploring the brain –the regulator of body system- is much harder than exploring neurons. We have to look at the motor area of the brain. This part of the cortex is largely responsible for the voluntary movement of the particular parts of the body. Every portion of the motor area corresponds to a specific locale within the body. If we were to insert an electrode into a particular part of the motor area of the cortex and apply mild electrical stimulation, there would be involuntarily movement in the corresponding part of the body. This model illustrates amount and relative location of cortical tissue that is used to produce movements in specific parts of human body. As we can see the control of body walking that requires relatively large scale and require little precision is centered in a very small space in the motor area.

2. What is Mechanical Meaning of Walking?

In terms of engineering, walking is a multi degree of freedom mechanism that have one joint at hip one joint at knee and one in ankle and working with an equivalent counterpart with a phase. Soles having a friction force with base that provide the movement of the body as in the tires of an automobile. Bones are rigid elements that carry the bodyweight and muscles are elastic actuators that drive the bones. After all this analogy with a traditional mechanism with the known values of leg and body weights, inertias, and specified values of speed of the mass center of the body, it is theoretically possible to consider it as a mechanism and analyze it but in practical applications it is so difficult to define exact values for the variables so we have to

simplify the mechanism to achieve an approximation to the solution. In terms of mechanics we apply two types of analyses to the mechanisms:
Kinematical Analysis and Kinetic Analysis.

2.THEORETICAL ANALYSIS

2.1. Kinematical Analysis

In our solution process, first we need our system to be modeled. The system can be modeled with different types of methods. We have chosen the Energy Methods to model our multi degree of freedom system.

2.2 - Energy Methods For Nonconservative Systems: Generalized Forces

Consider an n-degree-of-freedom system with generalized coordinates $x_1, x_2, \ldots, x_n$ acted on by external nonconservative forces. The system is moved through small displacements to a new arbitrary state specified by $x_1 + dx_1, x_2 + dx_2, \ldots, x_n + dx_n$. The changes in displacements are called virtual displacements. The work done by the nonconservative forces as the system moves through the virtual displacements is called the virtual work and is calculated using the usual definition of work done by a force. The virtual work can be written in the form

$$dW = \sum_{i=1}^{n} Q_i dx_i$$

The Q_i terms are called generalized forces. It can be shown that Lagrange's equations for nonconservative systems taken the form

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}_i}\right) - \frac{\partial L}{\partial x_i} = Q_i \qquad i = 1, \ldots, n$$

We can apply this solution method to our differential equations for governing the angular displacement values. Angular velocity and acceleration values can be obtained from those particular solutions.

Although we simplified the system to solve and find the data needed, it is still hard to solve it. So we began to research solutions for the simplest system bipedal walking locomotion without knee bent.

2.3 - Bipedal walking locomotion without knee bent:

The Model

A cartoon of our point-foot model is shown in Figure.1. It has two rigid legs connected by a frictionless hinge at the hip. The only masses are at the hip and the feet. The hip mass M is much larger than the foot mass m (M >> m) so that the motion of a swinging foot does not affect the motion of the hip. This linked mechanism moves on a rigid ramp of slope g . When a foot hits the ground (ramp surface) at heelstrike, it has a plastic (no-slip, no-bounce) collision and its velocity jumps to zero. That foot remains on the ground, acting like a hinge, until the swinging foot reaches heelstrike. During walking, only one foot is in contact with the ground at any time; double support occurs instantaneously.

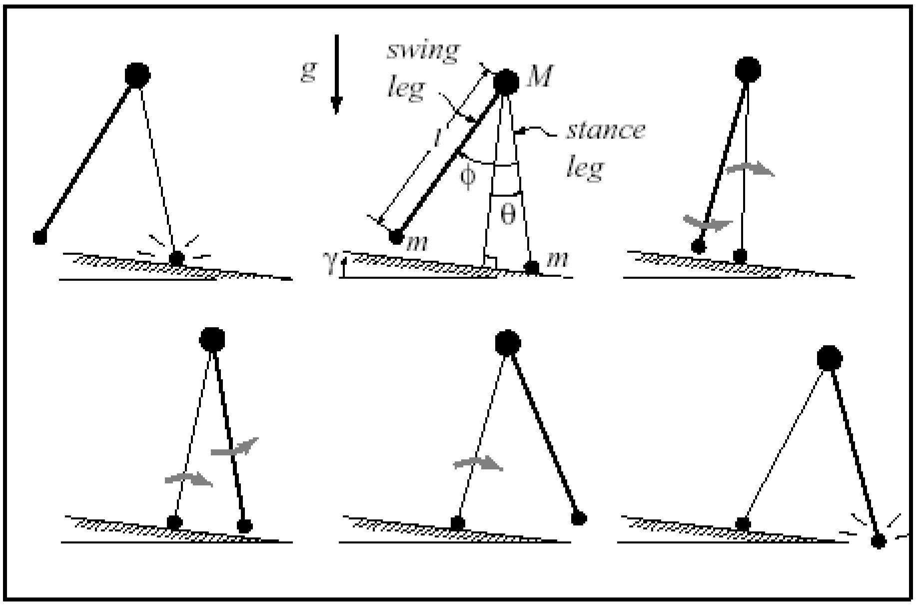

Figure 1. Geometrical Visualization

2.4.Deriving the equations of motion by Lagrange Method

$$KE = \frac{1}{2} M V_B^2 + \frac{1}{2} m V_C^2$$

$$KE = \frac{1}{2} M l^2 \dot{q}^2 + \frac{1}{2} m l^2 \dot{q}^2 + \frac{1}{2} m l^2 (\dot{f} - \dot{q})^2 + m l^2 \cos f \, \dot{q} (\dot{f} - \dot{q})$$

$$\frac{d}{dt}\left(\frac{\partial KE}{\partial \dot{q}} \right) = \left[M l^2 + 2 m l^2 - 2 m l^2 \cos f \right] \ddot{q} + \left[- m l^2 - m l^2 \cos f \right] \ddot{f}$$

$$+ \left[m l^2 \dot{f} \dot{q} \sin f - m l^2 \dot{f} (\dot{f} - \dot{q}) \sin f \right]$$

$$\frac{d}{dt}\left(\frac{\partial KE}{\partial \dot{f}} \right) = (-m l^2 + m l^2 \cos f) \ddot{q} + m l^2 \ddot{f} - m l^2 \dot{f}^2 \sin f$$

ANALYSIS OF POTENTIAL ENERGY

$$PE = Mgl \cos(q - f) + mgl \left[\cos(q - f) - \cos(q - f - g) \right]$$

$$\frac{\partial PE}{\partial q} = -Mgl \sin(q - g) - mgl \sin(q - g) + mgl \sin(q - f - g)$$

$$\frac{\partial PE}{\partial f} = -mgl \sin(q - f - g)$$

If we divide all the statements by M*l^2 and consider $b = \frac{m}{M}$;

The two coupled second-order differential equations of motion are given below for the swing phase of the motion, where $b = \frac{m}{M}$ q and f are functions of time t. These two equations represent angular momentum balance about the foot (for the whole mechanism) and about the hip (for the swing leg), respectively.

$$\begin{bmatrix} 1+2b(1-\cos f) & -b(1-\cos f) \\ b(1-\cos f) & -b \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \ddot{f} \end{bmatrix} + \begin{bmatrix} -b\sin f(\dot{f}^{2} - 2\dot{q}\dot{f}) \\ b\dot{q}^{2}\sin f \end{bmatrix}$$

$$+ \begin{bmatrix} (bg/l)[\sin(q-f-g)-\sin(q-g)] - g/l\sin(q-g) \\ (bg/l)\sin(q-f-g) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

These are the equations of motion for a simple double pendulum. We will study the special case where the `foot' is much smaller than the `body,' because of its conceptual simplicity, and because human feet are small compared to the rest of the body. Setting $b = 0$ (the limit as hip mass dominates foot mass) in the first equation of motion and dividing through by b in the second yields the two simpler equations which we use (equation 1 and a trig identity are used to simplify equation 2 also).

$$\ddot{q}(t) - \sin(q(t)-g) = 0 \qquad \textbf{. . . (1)}$$

$$\ddot{q}(t) - \ddot{f}(t) + \dot{q}^{2}(t)\sin f(t) - \cos(q(t)-g)\sin f(t) = 0 \qquad \textbf{. . . (2)}$$

In equations 1 and 2, we have rescaled time by $\sqrt{\frac{l}{g}}$. Equation 1 describes an inverted simple pendulum (the stance leg), which is not affected by the motion of the swing leg. Equation 2 describes the swing leg as a simple pendulum whose support (at the hip) moves through an arc.

These solutions are non-linear. Non-linear characterized systems are hard to be investigated but with some acceptance and restrictions, we can linearize the system. The linearized equations evaluated through perturbation with following initial assumptions, are given below in state form as :

$$\ddot{q}(t) - \sin(q(t)-g) = 0$$

$$g = e^{3}$$

$$q(t) = e \cdot q(t)$$

$$\dot{q}(t) = e \cdot \dot{q}(t)$$

$$f(t) = e \cdot f(t)$$

$$\dot{f}(t) = e \cdot \dot{f}(t)$$

Substituting these into equations 1 and 2 and expanding in a power series gives two governing equations with no order zero coefficient in e,

$$q_0(t) = \frac{1}{2}\left[q_0(0) + \dot{q}_0(0)\right]\cdot e^{t} + \frac{1}{2}\left[q_0(0) - \dot{q}_0(0)\right]\cdot e^{-t} \quad \textbf{...(3)}$$

$$f_0(t) = \frac{1}{2}q_0(t) - \frac{1}{2}\dot{q}_0(0)\sin t + \frac{3}{2}q_0 \cos t \quad \textbf{...(4)}$$

q_0, f_0, and t_0 are the first terms in the expansions of the state variables q, f, and the step period t as functions of the slope g.

$$q(t) \approx q_0(t) g^{1/3} \quad , \quad f(t) \approx f_0(t) g^{1/3} \quad , \quad t \approx t_0$$

1.3 – Bipedal Walking Locomotion With Knee:

For theoretical analysis of bipedal walking with knee, a model seen in Figure.2 is assumed to express the motion. The defined parameters and relevant equations of motion in accordance to Lagrange Method are given in the following as :

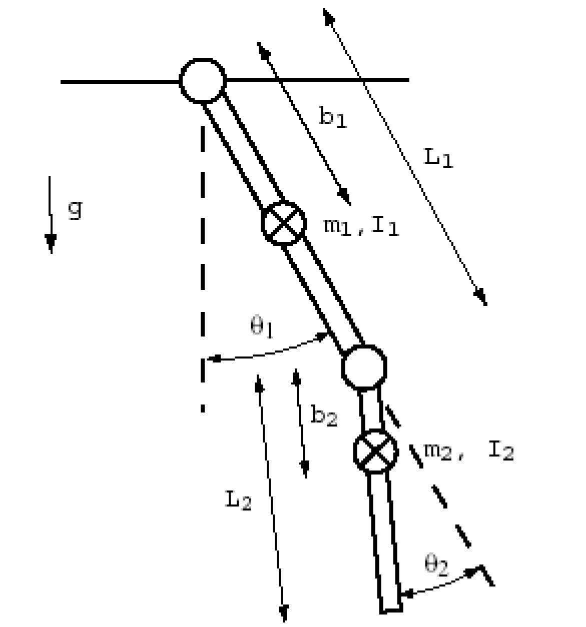

Figure 2.Modelling With Knee

$$J_0 = m_1 b_1^2 + I_1$$
$$J_1 = m_2 L_1 b_2$$
$$J_2 = m_2 L_1^2 + m_2 b_2^2 + I_2$$
$$J_3 = m_2 b_2^2 + I_2$$
$$G_1 = (m_1 b_1 + m_2 L_1) g$$
$$G_2 = m_2 b_2 g$$

$$KE = (\frac{1}{2}J_0 + \frac{1}{2}J_2 + J_1\cos q_2)\dot{q}_1^2 + \frac{1}{2}J_3\dot{q}_2^2 + (-J_3 - J_1\cos q_2)\dot{q}_1\dot{q}_2$$

$$PE = -m_1 b_1 g\cos q_1 - m_2 L_1 g\cos q_1 - m_2 b_2 g\cos(q_1 - q_2)$$

$$\frac{d}{dt}\left(\frac{\partial KE}{\partial \dot{q}_1}\right) = J_0\ddot{q}_1 + J_2\ddot{q}_1 + 2J_1\ddot{q}_1\cos q_2 - 2J_1\dot{q}_1\dot{q}_2\sin q_2 - J_3\ddot{q}_2 - J_1\ddot{q}_2\cos q_2 + J_1\ddot{q}_2\sin q_2$$

$$\frac{d}{dt}\left(\frac{\partial KE}{\partial \dot{q}_2}\right) = J_3\ddot{q}_2 - J_3\ddot{q}_1 - J_1\ddot{q}_1\cos q_2 + J_1\dot{q}_1\dot{q}_2\sin q_2$$

Using Lagrange's method results in the equations of motion:

$$\begin{bmatrix} J_0 + J_2 + 2J_1\cos q_2 & -J_1\cos q_2 - J_1\cos q_2 \\ -J_1\cos q_2 - J_3 & J_3 \end{bmatrix}\begin{bmatrix}\ddot{q}_1 \\ \ddot{q}_2\end{bmatrix} + \begin{bmatrix} -2J_1\dot{q}_1\dot{q}_2\sin q_2 + J_1\dot{q}^2\sin q_2 \\ J_1\dot{q}_1\dot{q}_2\sin q_2 \end{bmatrix} +$$

$$\begin{bmatrix} G_1\sin q_1 + G_2\sin(q_1 - q_2) \\ -G_2\sin(q_1 - q_2) \end{bmatrix} = \begin{bmatrix} T_1 \\ T_2 \end{bmatrix}$$

3.EXPERIMENTAL ANALYSIS OF WALKING MOTION

To have a real aspect of a healthy human walking, a series of experiments are made using a special designed prosthesis equipped with angle position measuring potentiometers, as seen in Fig.3. For these experiments, data values of four different people are measured and captured by computer and a statistical evaluation is done to find out the average values, which can be taken in consideration as significant characteristics of normal walking. After application, in contrary to many previous, generally model based mathematical studies; real measurements of both hip and knee angles of a healthy human being during bipedal walking under various circumstances are registered to make a certain decision of normal walking conditions

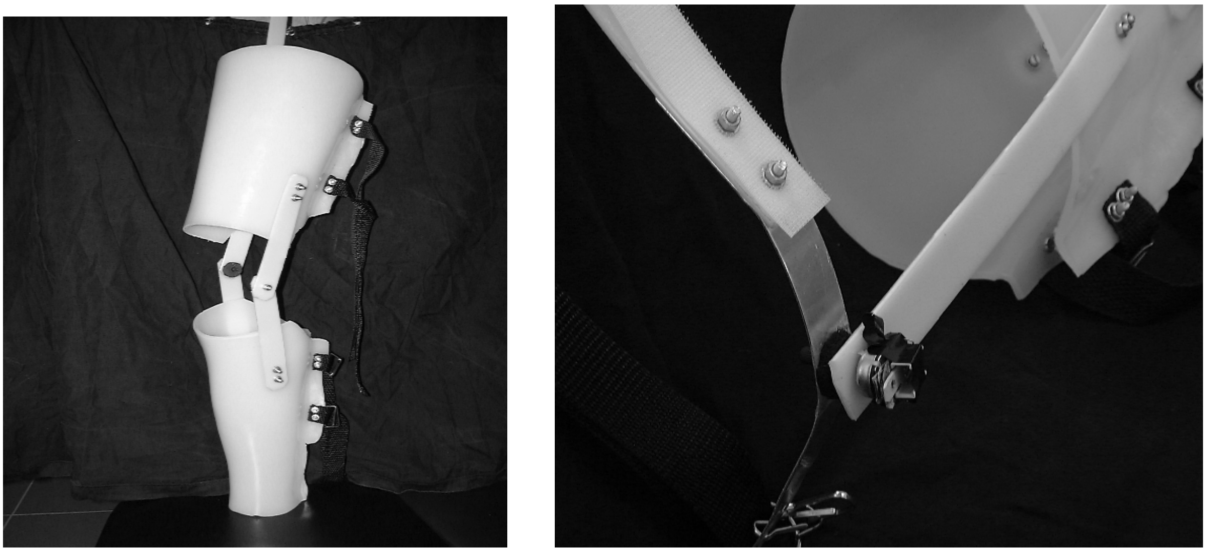

Figure.3 Designed prosthesis for measurements

4. APPLICATION OF TEST MEASUREMENTS

Various measurements are made both for hip and knee motions as seen in Fig.4. First of all, the characteristics and calibration (Voltage/Angle Curves) of analog potentiometers are carefully created for the relevant motion interval and a precise curve- fitting used as seen in Fig.5 After this registration the measured analog voltages of potentiometers are transferred as digital signals to a computer by a high performance, high speed Data Acquisition Card (Advantech 812-G) and saved into the hard disk as a data file using a convenient software program written in C++ language.

Fig.4.Test measurements of hip and knee motion

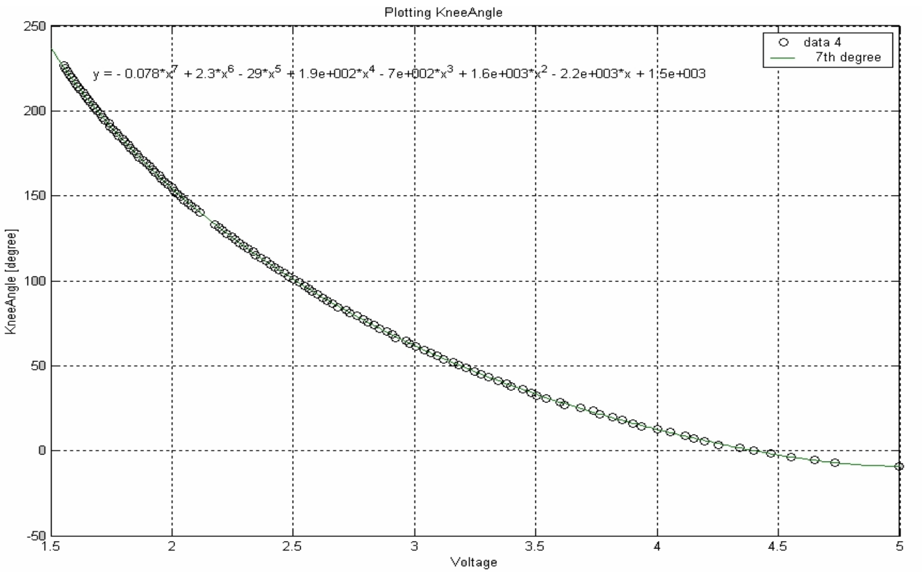

Figure.5 Calibration of knee-angle potentiometer

The transferred data of a test measurement stored as a file in hard disk is then visualized as a curve through MATLAB program. The original picture of a taken motion is modulated and disturbed with high frequency noise effects. To eliminate these noise signals, the cut off frequency of the issue is determined by using an FFT (Fast Fourier Transform) algorithm through MATLAB. In Figure.6 a Bode-Plot of Fast Fourier Transformed signal is given in logarithmic frequency scale. According to this plot a cut off frequency of f = 20 Hz is found to be a convenient value for the process.

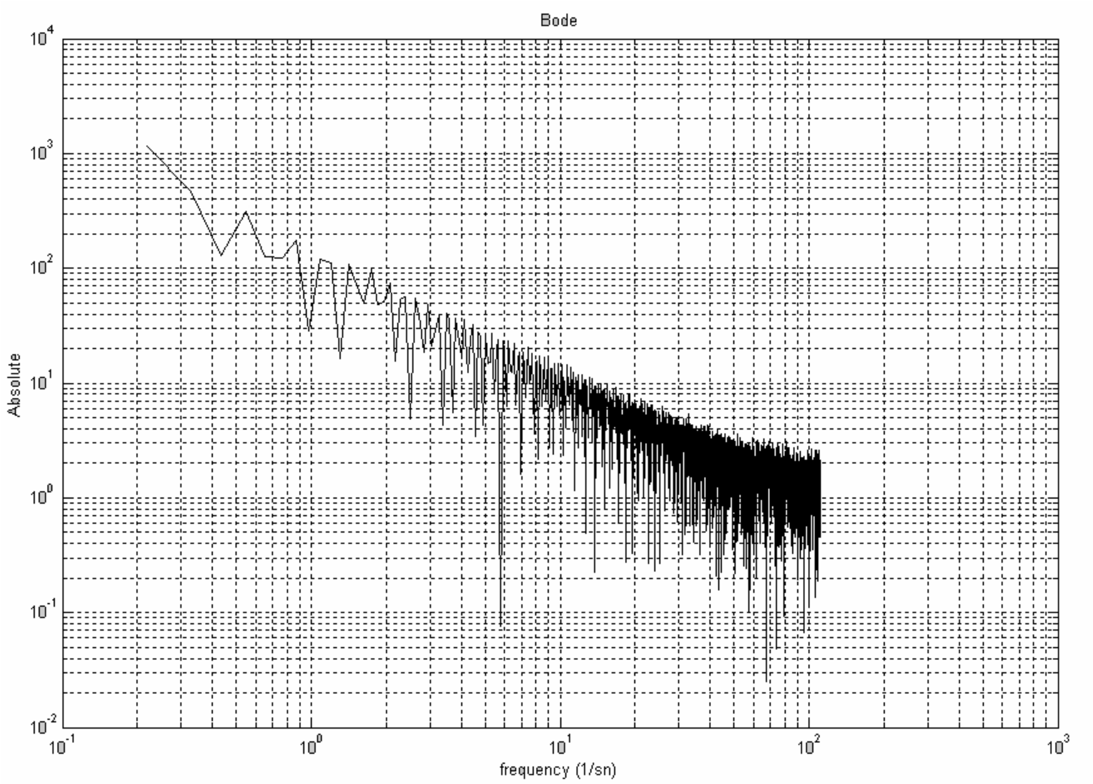

Figure.6 Bode plot of FFT applied knee - motion signal

5.CONCLUSIONS

In Figure.7 the original and filtered signals of knee and hip motions, taken from a healthy person, are given. Various tests and registrations from various persons, under various conditions such as up and down walking, stair–climbing, straight walking, running, are made. From various charts it is recognized, that the human beings without any disability, have similar periodically motion behaviors. On the other hand for a healthy human, it has been found an exact relationship between the hip and knee motions, so that this fact can be used for improving an optimal prosthesis for an upper knee- amputee person, whose Tibia can then be stimulated via a feed back motor to create a synchronized motion with hip and so the condition for a normal walking procedure.

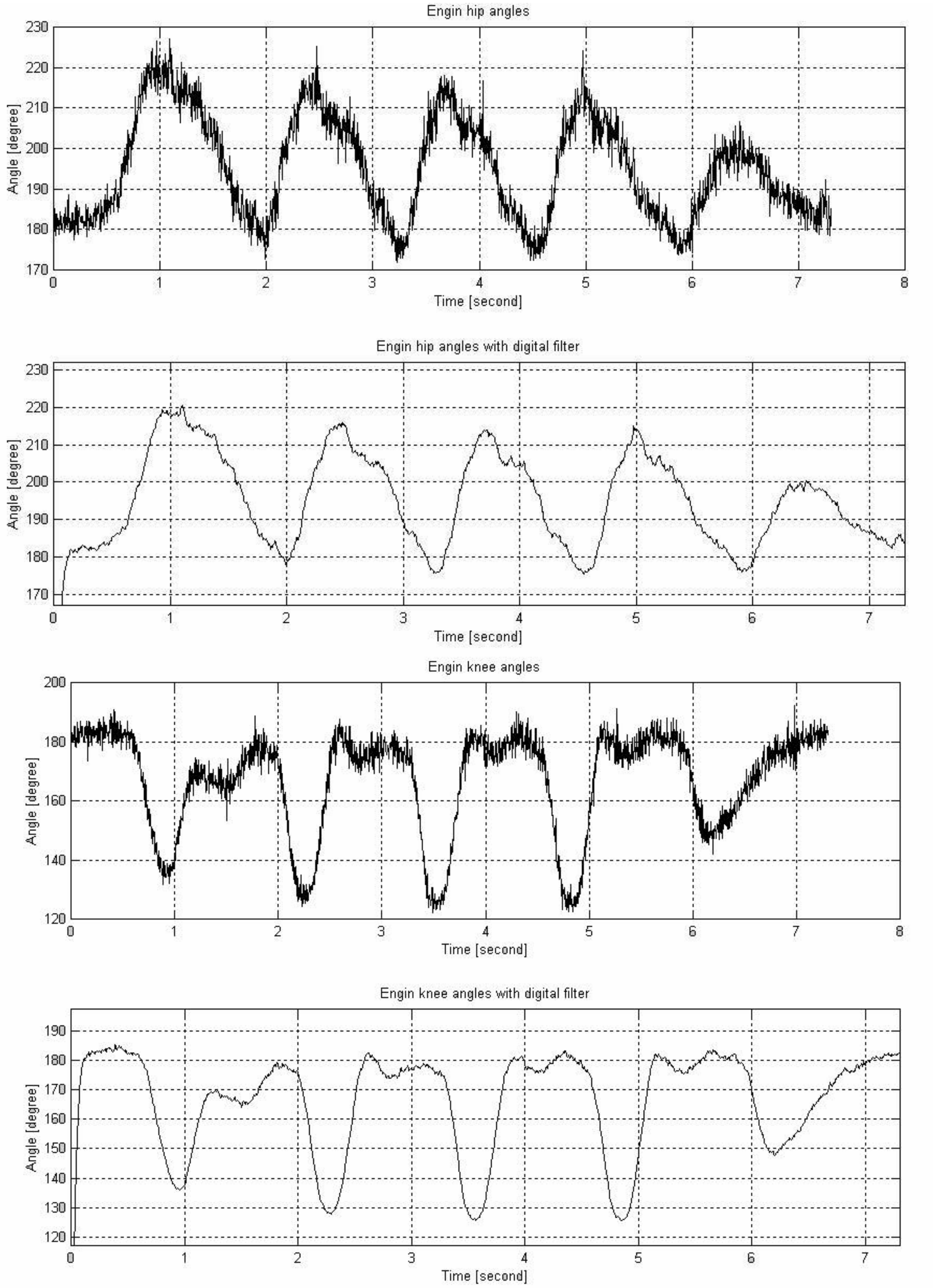

Figure.7 Original and filtered motion signals (Knee and hip)

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