Modelling, Analysis and Fabrication of Supporting System for Lower Limb

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Abstract— ***This work is an attempt towards the development of supporting system for afflicted human locomotion. The mathematical modelling of natural human locomotion its analysis and its utilization in realizing the supporting system for afflicted human locomotion and its mathematical modelling is the primary objective of this paper. Special emphasis has been given to average value based approach in the development of mathematical model for the natural human locomotion by suitably modifying the conventional infinite series (n^{th} order linear differential equation with constant coefficients). The data's required for developing a mathematical model is acquired through optical measuring techniques. The optical measuring technique improves the precision of reading up to duration of 0.025 secs. The important inferences derived from the analysis of natural human locomotion are used in the design and analysis of artificial walking device.***

Keywords— assistive device, average value base, optical technique, PIC

I. Introduction

Artificial walking aids have found wide application as a helping device for the afflicted human beings. It will help a lot for compensating the limitations of the handicapped for delivering their day to day work thereby reducing their dependences with others. So many types of walking aids ranging from very simple one to highly complex ones in operation are widely available presently. The most desirable operating characteristics of such a system will be the one, which exhibits a characteristic similar to that of the human locomotion.

The presently available popular devices (for example HAL-Hybrid Assistive Limb, exoskeleton etc) are working well in this direction. The need and utility of these devices are increasing day by day. Not only that the medical field demands more improvements in their operational and performance characteristics also. Expected improvement in the characteristics can be brought out only through a thorough and accurate analysis of human locomotion and, it is towards these aspects, the thesis is aimed at.

The existing HAL [1] is controlled by biological and motion signals. Presently they produce torque corresponding to human muscle contraction torque (myoelectricity). In addition, the viscoelasticity adjusted in proportion to operators' viscoelasticities, estimated from motion information. BLEEX [2] is the first energetically autonomous lower extremity exoskeleton (another assistive device) capable of carrying a payload up to 75 kgs. BLEEX works at speeds up to 1.3 m/s and shadow the operator through numerous maneuvers without any human sensing or pre-programmed motions.

A new wearable antigravity muscles support system [3] supports antigravity muscles around the knee and hip joint. Here a posture based control algorithm without using biological signals is implemented. Sai K banala and et.al [4] propose a device to assist persons with hemiparesis to walk. The device is passive and has simple patient-machine interface. Jerry E Pratt and et.al [5] developed a one degree of freedom exoskeleton called Roboknee. In Roboknee user intent is determined through the knee joint angle and ground reaction forces.

For people with weakness or paralysis, a standard Knee Ankle Foot Orthosis (KAFO) is required to support the limb during locomotion. In connection to this many of exciting KAFO's support the limb by locking the knee in full extension throughout the gait cycle to prevent the leg from collapsing while weight bearing. Kenton R. Kaufman and et.al [6] and [7-9] improved KAFO by providing an articulated knee joint system that reduces the metabolic energy requirements during gait. This orthosis provides knee stability during stance while allowing free knee motion during the swing phase of gait. The proposed model is **simple, cost effective and easily implementable**. The main functions of the developed model are to **resist flexion in stance while allowing free knee extension and Permit free knee rotation in flexion and extension when the braced leg is unloaded in swing.**

Even though these literatures cited through the citations mentioned in [1] to [09] are specifically telling various things but a coordinated systematic approach towards the development of the control aspects, characteristics, mathematical models of a system which can assist for the smooth and easy function of a handicapped (afflicted human locomotion) is not specifically seen. Hence an attempt towards such a coordinated work is justified both on technical and humanitarian points of view.

The aim of this paper is to propose a model based analysis technique to facilitate another analysis method. This attempt is especially aiming towards the development of a mathematical model based upon the experimental results conducted upon different subjects.

The important steps involved in the paper can be divided as:

a) Conducting a positional analysis of human locomotion by optical methods.

b) Experimental determination of displacement characteristics of human locomotion system repeatedly on different subjects by considering time as the independent variable.

c) Utilizing the above determined data for the development of a mathematical model and subsequent generalization of the characteristic of model as an infinite series.

d) Formulation of the general operational characteristics using the experimental readings.

e) Designing a mechanical system for the practical implementation of the above

f) Designing an electronic driving system having operational characteristics similar to the above developed natural dynamic models.

g) Designing appropriate control systems which involves software packages and microcontroller based control, switching, locking and unlocking circuits etc as subsystems. The control system is mainly responsible for the sequencing and synchronizing steps of human locomotion.

h) A software program using MATLAB syntax will compare the operational characteristics of the artificially developed human locomotion model so as to have a minimum error possible.

i) Experimental verification of the system incorporating the drive, control module and mechanical structure by conducting experiments and determining the displacement characteristics by considering time as the independent variable.

j) Comparisons of the operational characteristics of the system with that of the average human locomotion. Repetition of the step (j) for conformation.

II. Development of a Mathematical Model (Human Locomotion)

The idea involves is the continuous observation of the displacement of human legs of different specimen by video analysis. The positional data of the human leg is monitored at each and every 0.025 seconds. The complete set of readings corresponding to the leg positions which determines the operational behaviour of human locomotion is observed for a time period T_i to T_f and recorded.

Suppose that certain process variables say angular displacement of the knee joint and the hip of human leg determine the system operational behavior may be observed for a time period say from T_i to T_f and the readings are recorded. The variation in the values of these variables shows the actual dynamics of the human locomotion. The objective of the work is to develop a linear mathematical model for the above dynamics. The procedure for deriving these factors is explained in detail as follows:

a) Identical average value sectors

From the observed values of the angular displacements of the hip and the knee, Find out certain sectors (eg: time period from T1 to T4 or Time period from T2 to T3 etc) such that the average values of these sectors are the same. These sectors are called the identical average value sectors or primary sectors and the average value corresponding to these sectors are called primary averages.

b) Secondary sectors

For further experimentation with the observed values inside the primary sectors, inner secondary sectors exists which yields the average value which are slightly and independently different from the average value of the primary sectors. These are named as secondary averages.

c) Tertiary sectors

Similarly some tertiary sectors are identified inside each of the above secondary sectors which further yields slightly different average values from the respective average values of the secondary sectors. They are termed as tertiary averages.

d) Special sectors

In reality, possibilities cannot be ruled out for some small time sectors called special sectors which exhibit widely different average value from the uniform average value of the primary sector.

Derivation of Input-Output Relationship

The variation of the system process variables in the output is due to the structural changes occurring in the system. The so changed structure is the main reason for the so reflected dynamics. In such cases, it is always possible to have a relationship between the input and output dynamics or rather an equality relationship incorporating the input and output values and structural variational parts exists. Assuming the system as linear, the following empirical relationship is guessed.

As indicated above, It will be quiet conforming to think that the output dynamics is a linear combination of components involving a base average value, A, a variational part over the above average value, $\Delta 1A$, a factor containing the variational part in $\Delta 1A$, ,$\Delta\Delta 1$, and so on. It can be stated in another way that the output is a combination of a base average value and infinite number of hierarchically considered variational terms. To make it more clearly, these variational terms must be multiplied by the factors M_1, M_2, M_3…….. to take care of the effect of variable structure or the input-output relationship can be represented empirically as

$BQ=M_1A+M_2\,\Delta 1A+M_3\Delta_2A+$ ………….

To accommodate the dynamics contributed by special sectors, a constant (K) is also considered. Strictly speaking, the input part also has to be considered as a summation of infinite number of terms involving a base value and subsequent variational terms. But to avoid practical complexity, only one term i.e. base term alone (Q along with the factor B) is considered for the input dynamics.

In the light of above explanations, the input-output dynamics of the sub subsystem can be represented as

$BQ=M_1A+M_2\Delta 1A+M_3\Delta_2A+K$ +…….. (1)

Procedure for Finding The Variational Parts:

The steps to be followed to obtain the variational parts are as under:

1. To find $\Delta 1A$:

a. Obtain the average value of the primary sector.

b. Divide the primary sector into secondary sectors and find the secondary averages.

c. Obtain the differences between the primary averages and the secondary averages.

d. The averages of these differences are $\Delta 1A$.

2. To find Δ_2A:

a. Divide the secondary sectors in to tertiary sectors.

b. Determine the tertiary averages.

c. Obtain the differences between the secondary averages and tertiary averages.

d. The average of these differences is Δ_2A.

Experimental Determination (Normal Walking)

The above mentioned general concept has to be implemented with respect to the natural human locomotion. This can be achieved by substituting the appropriate variables in place of general variables i.e. the specific variables pertaining to angular displacements of the Knee and the Hip of human locomotion.

From the observed readings (knee joint angle and hip joint angle) a proposed average value based algorithm as mentioned above is applied on the complete set of data. From the above proposed method the base average, first change in base average and second change in base average of the mathematical model developed is calculated and are summarized in the Table 1 shown below.

Primary Sector	A Region of values of Angular displacements corresponding to frame no 1 to 200		B Region of values of Angular displacements corresponding to frame no 201 to 400		C Region of values of Angular displacements corresponding to frame no 401 to 600	
	Knee	Hip	Knee	Hip	Knee	Hip
Base Average Value for left leg corresponding to angular displacement	167	164	165	164	164	163
Base Average Value for Right leg corresponding to angular displacement	164	163	164	164	165	164
First Variational Term for left leg corresponding to angular velocity	6.3	2.79	3.9	2.51	6.9	2.81
First Variational Term for right leg corresponding to angular velocity	4.3	3.2	3.9	2.05	7.3	2.2
Second Variational Term for left leg corresponding to angular acceleration	15.09	8.98	17.88	8.89	16.9	8.30
Second Variational Term for right leg corresponding to angular acceleration	17.75	8.17	17.83	9.2410	15.99	9.23
Locking time corresponding to left leg	800 mille seconds					
Locking time corresponding to right leg	800 mille seconds					
Unlocking time corresponding to left leg	525 mille seconds					
Unlocking time corresponding to right leg	525 mille seconds					
Time between locking and unlocking	0.36 seconds					

Formulation of Mathematical Equations:

By using the above terms an equation for Primary Sector A is formulated for both left and right leg knee angle as follows

$P1^*(Bavg_A)+P2^*(\Delta Bvg_A)+P3^*(\Delta^2 Bavg_A)=$ distance covered corresponding to Primary Sector A

The constants P1,P2and P3 represents the physical parameters of the system

Simillarly for Primary Sectors B and C

$P1^*(Bavg_B)+P2^*(\Delta Bvg_B)+P3^*(\Delta^2 Bavg_B)=$ distance covered corresponding to Primary Sector B

$P1^*(Bavg_C)+P2^*(\Delta Bvg_C)+P3^*(\Delta^2 Bavg_C)=$ distance covered corresponding to Primary Sector C

Hence the general equation for the characteristics of human locomotion can be represented as

P1*(Base Avg_X) + P2*(First change in Base Avg_X)+P3*(Second change in Base Avg_X) = distance covered in Primary SectorX ----(4)

The proposed method is applied to the normal walking case and the mathematical model of the variation of knee joint angle is developed as below.

The normal walking video is captured for a finite time i.e. 20 seconds. The entire data base is divided into three Primary Sectors of 5 seconds each as explained above. The proposed method is applied, base value and variational terms are obtained for each Primary Sector as shown in Table-1 The entire distance covered in 20 seconds is 14.4 Meters and for each Primary Sector of duration 5 seconds the distance covered is 3.6Meters.

The following six equations i.e. equation 5-7 for left leg and equation 8-10 for right leg are formulated from the data collected as shown in Table-1

167*P1 + 6.3* P2 + 15.09 *P3 = 3.6 -----(5)

165*P1 + 3.9* P2 + 17.88 *P3 = 3.6 -----(6)

164*P1 + 6.9* P2 + 16.9 *P3 = 3.6 -------(7)

164*P1 + 4.3* P2 + 17.75 *P3 = 3.6 ------(8)

164*P1 + 3.9* P2 + 17.83 *P3 = 3.6 -------(9)

165*P1 + 7.3* P2 + 15.99 *P3 = 3.6 ------(10)

Here the relation between a dependent variable and independent variable is not accurately available from theory. The optimum form of relation and the 'best ' set of numerical coefficients, given a set of measured data is found using MATLAB. The values of the constants are obtained by solving the above equations. For the subject consider for experimentation we obtain the values of P1,P2,P3.

To make the cummulative angular displacement of the human locomotion smooth a Newton's forward difference interpolation technique or Newton Gregory Formulae is used to approximate a given function, whose values are known at N+1 tabular point, by a suitable polynomial $P_N(x)$ of degree N which takes the values y_i at $x=x_i$ for i=0,1,2,……. This enables us to find the intermediate values.

III. Inferences of Human Locomotion Positional Analysis

From the above optical analysis techniques on the human locomotion the following information regarding its operational characteristics are derived. Each leg knee is found to make angular displacement of 55^0 in slow walking mode it will vary to 48^0 in the case of normal walking mode, 35^0 in the fast walking. In the case of hip the above values are 25^0,20^0 and 15^0 for slow, normal and fast walking modes respectively.

The directions of angular velocity of hip and knee are opposite. The total gait cycle has 53 frames (each frame 0.025 seconds) i.e. 1.325 seconds out of which stance phase is for 800 msecs and swing phase for 525 msecs. From the analysis we also derived a conclusion that the time interval between these two operations i.e. locking and unlocking is 0.36 seconds. Once again it has to say that details inferred above are taken in an average manner from the positional analysis of human locomotion upon 300 subjects. These details are shown in the Table 1 for more clarity.

These values are taken for the design and fabrication of the assistive device. The angular displacement, angular velocity and angular acceleration are decided and adjusted by adjusting the current of the driving circuit. However some trial and error experiment is also done to make its characteristics similar to that given by the model.

IV. Practical Realization

Practically the system is realized by adjusting the velocity, locking time etc by making suitable adjustments in software, thereby making the device to exhibit similar characteristics to that of an average natural locomotion. This is achieved by comparing the locomotion characteristics of the practically developed one to that of the average natural human locomotion.

This adjustment is achieved more or less on a trial and error basis adjustment in the software (by adjusting the delay and angular velocity).

The walking system contains the following subsystems as mentioned below in an abstract way.

a) Mechanical structure as counterpart for human leg
b) Artificial locking system for both legs
c) Driving system for the leg movement
d) Central control system module to synchronize (PIC Microcontroller)

The system contains software package/ the electronic module for locking/unlocking and leg driver mechanism. It basically consists of systems like

1) Relay & relay Driver module
2) Keypad module
3) Microcontroller with LCD display
4) Power regulator
5) Foot switches
6) Proximity Sensor (IR)

The operation of the driving circuit is explained briefly as follows and shown in fig 1:

The electronic module consists of six relay and relay driver circuits. Relay 1 is connected to one leg DC motor, relay 2 is connected to other leg DC motor, and both this relays are used for leg movement. Remaining 4 relays are used to lock/unlock both legs. Relay 3 is used for locking the knee joint of one leg, relay 4 for unlocking the same leg. Similarly relay 5 for locking the knee joint of second leg and relay 6 for unlocking the same leg. Key pad provision is made on the front panel of the electronic module to adjust the Operation of all the DC motors (total 4 – 2 for leg movement and 2 for locking/unlocking). With the help of key pad the user can adjust the time delay between the on and off times of relays.

The device is equipped with foot switches. The foot switches on and off the respective relays for locking/unlocking the knee joint. In the final structure the foot switches are embedded into the foot shoe. The principle of operation of switch is when both the foot is on the floor i.e. stance phase the relay 3 and relay 5 will on and both legs knee joint will lock. When the user wants to make the movement, according to the natural gait analysis one leg knee joint should unlock so relay 4 will on and the DC motor corresponding to that leg should activate for the motion i.e. relay 1 should on. When that particular leg is on the floor

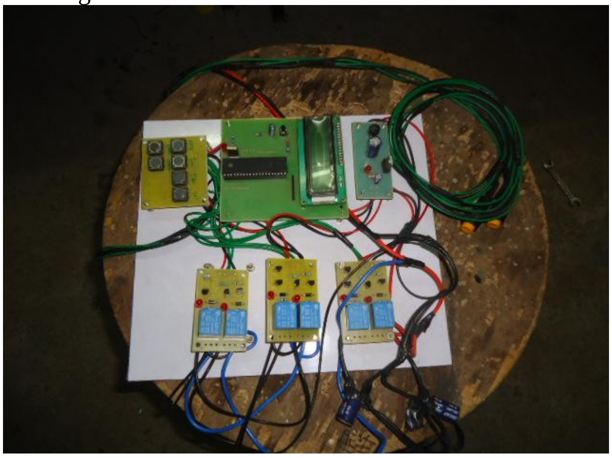

Fig1. Electronic module for the supporting device

Fig 2. Mechanical structure of the walking Device

then relay3 is on to lock it. Similarly for the other leg relay 6 will on to unlock and relay2 will on to actuate the DC motor corresponding to that leg for the motion. So the on and off of the relays are controlled by the microcontroller. For the purpose of making the walking aid work automatically the pulse to the relays are sent by the foot switches embedded below the foot.

Briefly it can be stated that the operations performed by the foot switches, electronic relays, motors in coordination with the associated software module works in closed loop form.

In addition to the above four motors two more motors are used for the movement of hip and these motors are controlled by two relays using PIC Microcontroller. Proximity sensor is used for the correct alignment of leg during stance phase so that the knee is locked smoothly without any jerk.

Since the characteristic of human locomotion is distinct for each individual the model is based on average characteristics for generality. The average characteristics are arrived from the experimental data obtained from different subjects. The experimentation was carried out on the hardware model developed for numerous numbers of times and for different durations at different instants of time.

A similar experiment as that did for natural human locomotion is carried out on the fabricated assistive device. The same optical analysis technique is used for tabulating the values of angular displacements of the hip and the knee of the assistive device. A mathematical model is developed by making use of the proposed average value based algorithm by calculating the base value, first change in base value and so on from the tabulated reading of the angular displacements of assistive device locomotion. Both the mathematical models are compared and a very good similarity is observed.

IV. Conclusion

The importance of artificial walking aids for afflicted human beings is all the more great importance as far as humanitarian aspects are concerned. No doubt any work pertaining to their modification and improvement will definitely increase the compensating abilities of such devices for the limitations of handicapped ones for delivering their day to day work. Hence any attempt to make the related aspects of walking aids such as their design, analysis, improvement/modification easier, simpler, systematic and standardized are quite welcome. The work of this thesis is in this direction and therefore justified.

The experimental procedure for the model development of human locomotion has been conducted. An optical device (video camera) is utilized for this purpose. The data regarding the positions of the human leg below the knee, above the knee while in motion are captured in video frames and successfully detected the angular displacements, angular velocities and angular accelerations of human leg. These data's are successfully utilized and an infinite series mathematical model is developed. Data's corresponding to normal walking and also walking on tread mill is utilized effectively. The model developed is also validated successfully.

By using the analysis of the model developed an artificial assistive device and a suitable driving system has been realized practically. The characteristics of the driving system such as locking/unlocking of the knees, synchronized and sequential operations of the knee and the hip have been successfully done. The assistive device developed is simple, cheap and robust.

A similar experiment, as that did for natural human locomotion is also successfully completed upon the fabricated assistive device by using optical devices (video camera) again. By using the data a mathematical model is formulated in a similar manner. Both the mathematical models:

1. Developed for natural human locomotion.
2. Developed for artificially constructed assistive device are compared and a very good similarity is observed.

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