

# Modelling Analysis and Realization of a Supporting System for Afflicted Subjects

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**Abstract:** Walking assistive devices have wide range of demand through out the year all around the globe. A simple linear mathematical model connecting input output relationship for both angular displacement and knee moment has been derived. Derived mathematical model for knee moment has been compared with the knee moments obtained from newton's equations of motion. The results obtained is validated by comparing with the fabricated structure results.

**Keywords:** Average value based, moment, Primary sector, Secondary sector, Tertiary sector, Walking assistive device

## 1. INTRODUCTION

Locomotion have prior importance for any human beings in their life. Hence walking assistive devices are always a boon for the afflicted human beings. At present, variety of walking devices are widely available for different gait irregularities. But the most preferred one is selected depending on the suitable gait characteristics of a subject that it can exhibit. The present walking assistive devices which are more popular and widely available in markets viz., HAL-Hybrid Assistive Limb, exoskeleton, have more focus on the suitability of gait characteristics. Further improvements can be made on walking assistive devices if and only if a perfect gait analysis is carried out and new methods are implemented. A robot suit HAL (hybrid assistive limb) [1] has been developed by T Hayashi et.al, as an walking assistive device for lower limbs. Here the assistive device will develop torque corresponding to myoelectricity signal which has biological information to produce muscle contraction for required torque. BLEEX [2] demonstrated first energetically autonomous, seven degrees of freedom, hydraulically actuated walking assistive device that can carry the payload. A wearable walking helper has been proposed by [3] Takahiko et. al, whose function is to support below hip antigravity muscles. Here the required knee moment for a specific model is calculated based on the antigravity term of necessary knee moment.

An assistive device, which can reduce or eliminate the effects of gravity, for persons with hemi paresis to walk was proposed by [4] Sai et. al., Jerry E Pratt et.al [5] developed a Rob knee which can be worn on the knee and can be used to climb stairs and in acute knee bends during payloads.

This has one degree of freedom and requirement of torque that has to be developed at knee is sensed by knee joint angle and ground reaction forces. knee ankle foot orthosis (KAFO) supports the lower limb and enable Partially or fully paralysed people to regain their locomotion. Kenton et.al [6] [7-9] proposed an improved KAFO for an articulated knee joint system that reduces the metabolic energy expenditure during walking. This KAFO improves the knee stability during stance phase by locking the knee and unlocks the knee during swing phase of the gait cycle.

The development of an efficient KAFO relies on the research in biomechanics of gait cycle. Biomechanics of gait cycle deals with forces and moments [10] [11] especially, forces and loading at the foot [12] [13] and at the hip [14] [15]. Ground reaction forces and positional co-ordinates are measured and located using markers and force plates [16]. Inverse dynamics models are used to determine the force and moments at different joints using ground reaction forces [17] [18]. Angles and positional co-ordinates are used to determine velocity and acceleration using forward dynamic models [19] [20] [21].

Even though many vast developments in KAFO has been cited in literature, a general, mathematical models of a system which can assist for the smooth and easy function of a handicapped (afflicted human locomotion) is not specifically seen This work focus on the comparison of two methods: 1) Newton's equations of motion 2) Average value based method.

Gait cycle of a normal male subject is recorded using a high resolution, 40 frames per second, camera. The gait cycle is recorded for every 25 milli seconds interval. Here the main focus of gait cycle recording is for observing angular displacement of knee joint. knee joint angular displacement is recorded for a time period of  $T_i$  to  $T_f$  seconds. From the tabulated reading it was observed that the angular displacement varies with time, which

## 2. Average value based model development

### 2.1. Linear Mathematical Model

represents the dynamic state of the subject. This enhances the requirement for developing a linear mathematical model for the dynamics state. Mathematical model is developed using a method similar to finite difference method. For this the total time frame has to be divided into certain sectors viz., primary, secondary, tertiary sectors.

The recorded knee angular displacement are divided into certain sectors depending on the equality of the average values. For a general division of sectors, time frame can be used as reference. The number of sectors with same average values are grouped under the category primary sectors and corresponding average values of these sectors are named as primary averages. Primary sectors are further categorised into secondary sectors which have average value which are slightly different from the average value of primary sectors. The average value of this sectors are so called first variational term. Similarly secondary sectors are further categorised into tertiary sectors which have average values which are slightly different from the average values of primary sectors. The average value of this sectors are so called second variational term

An input output relationship has to be created using the categorized sectors for further study of the dynamics of the system. Assuming the system to be linear the following input output relation ship is assumed. The output is a function of base average value, first variational change from base average value, second variational change from first variational term and so on. Base average value is the average of difference between primary sector average and total average. Similarly first variational term is the average of difference between primary sector average and secondary sector average. The variational terms has to be multiplied by the some factors  $N_1, N_2, N_3$  to make the relation linear. The input output is represented as

$$\text{Input} = N_1(\text{Base average}) + N_2(\text{First variational term}) + N_3(\text{Second variational term}) + \dots$$

The input part should also be considered as a summation terms involving base average value and variational terms. But to avoid practical complexity, it is considered as only one term.

## 2.2. Procedure for Finding the Variational Parts:

### To calculate first variational term :

- Split the whole data into feasible number of primary sectors and calculate its average.
- Primary sector is again splitted into feasible number of secondary sectors and calculate its average
- Difference between primary averages and secondary averages is computed.
- The average of the difference between primary and secondary sector averages is the first variational term.

### To Calculate second variational term:

- Secondary sectors obtained above are splitted into feasible number of tertiary sectors.
- Calculate the average of tertiary sectors.
- Difference between the secondary averages and tertiary averages has been computed
- The average of the difference between secondary and tertiary sector averages is the second variational term.

## 2.3. Inferences of Human Locomotion Positional Analysis

Knee angle is found to be  $55^\circ$  during slow walking mode,  $48^\circ$  during normal walking mode and  $35^\circ$  in the fast walking. The hip angles are  $25^\circ$  for slow walking,  $20^\circ$  for normal walking and  $15^\circ$  for slow walking. The directions of angular velocity of hip and knee are opposite. The angular displacement, angular velocity and angular acceleration are measured and corresponding motion in walking assistive devices are obtained by supplying equivalent amount of current to motors through driving circuit. However some trial and error methods are adopted for making the characteristics similar to that of the given model.

## 3. Modeling Approaches

### 3.1. Kinematic and kinetic analysis using newtons equations of motion

A human gait cycle has three phases namely heel contact, midstance and propulsive phases (fig. 1). Heel contact, Midstance and Propulsive phases constitutes 27%, 40%, 33% respectively of the gait cycle. During heel contact and toe off phases, ground reaction forces are acting at foot as per newtons second law of motion. This ground reaction forces cause reaction forces and moments at the ankle, knee and hip joints. Moments and forces at the joints has to be determined for the design and development of the orthosis. Here newtons equation of motion for dynamic state is used for calculating the moments and forces acting at the joints.

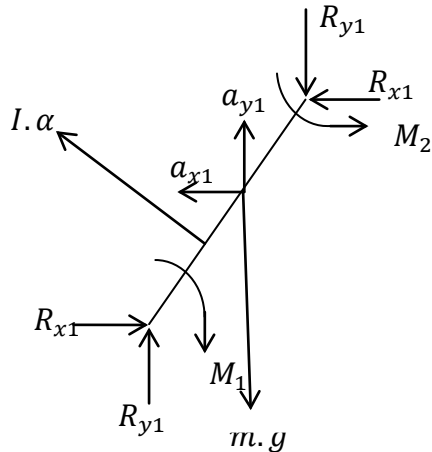


Fig 1 Three Phases of gait cycle

Reaction forces and moments are calculated for a male subject with weight 80kg and height 6 feet. Length and mass of the leg segments are calculated using anthropometric ratio obtained from winter 1990. Reaction forces at the heel and toe region are measured from force plates that are installed in gait labs, where high resolution cameras are installed to capture the

**Table 1** Calculation of moment and reaction force for 2<sup>nd</sup> 3<sup>rd</sup> and 4<sup>th</sup> frames

Frame	Time (sec)	m <sub>leg</sub> (kg)	a <sub>COMX</sub> (m/s <sup>2</sup> )	a <sub>COMY</sub> (m/s <sup>2</sup> )	R <sub>Xleg</sub> (N)	R <sub>Yleg</sub> (N)	r <sub>leg</sub> (mm <sup>4</sup> )	α <sub>2</sub> (rad/sec <sup>2</sup> )	L <sub>2</sub> (m)	θ <sub>2</sub> (deg)	M <sub>2</sub> (N-m)
2	0.014	3.72	7.99	0.37	-0.8156	15.597	0.1359	-46.59	0.45	38	7.568
3	0.029	3.72	4.97	-0.29	7.16	8.55	0.1359	-65.29	0.45	37	3.744
4	0.043	3.72	2.66	-1.25	11.82	2.24	0.1359	-77.66	0.45	36.7	3.82



**Fig 2** Resolved forces and moments on a left leg segment during swing phase

human locomotion. Markers are placed on different places on the body for recording x and y position of the segment relative to a reference frame. This x and y co ordinates are fitted using curve fitting method in mat lab and obtain a quadratic, cubic or polynomial.

The resolved forces and moments acting on a right leg segment during swing phase is shown in fig.2.

Newton’s equations of motions for dynamic state is

$$\left. \begin{aligned} (\Sigma F_x)_i &= m_i a_{xi} \\ (\Sigma F_y)_i &= m_i a_{yi} \\ (\Sigma M_{COM})_i &= I_i \alpha_i \end{aligned} \right\} i = 1,2,3 \quad (1)$$

F<sub>x</sub> is the reaction force acting along x direction, F<sub>y</sub> is the reaction force acting along y direction, a<sub>x</sub> is the acceleration acting in x direction, a<sub>y</sub> is the acceleration acting in y direction, m is the mass of the leg, M<sub>com</sub> is the moment about centre of gravity I is the moment of inertia and α is the angular acceleration of the leg.

A mathematical input output relation is obtained using the base average value method. The moment at the knee is equated to product of moment of inertia and angular acceleration. The equations obtained are

$$4.028N_1 + 4.835N_2 + 0.78N_3 = 2.38 \quad (2)$$

$$5.044N_1 + 11.901N_2 + 7.487N_3 = 1.28 \quad (3)$$

$$5.014N_1 + 7.142N_2 + 2.93N_3 = 0.66 \quad (4)$$

The values N<sub>1</sub>, N<sub>2</sub>, N<sub>3</sub> are obtained by solving above equations using matlab. This values corresponds to moment at a particular positional data.

#### 4. Experimental Determination (Normal Walking)

An assistive device is fabricated using aluminium material (fig 3). High torque electric motors are assembled at thigh and angle joints. A locking mechanism using electrical dc motors and rack and pinion arrangement is assembled at knee joint. The function of locking mechanism is to lock the knee during locomotion so as to resist the bending of the knee while it is unlocked during sitting position or at situations where bending of the knee is required. A set of 600 angular displacement values has been recorded using camera and locking and unlocking time for knee joint are tabulated. The tabulated values are fed as input to the average value based model and the base average, first change in base average and second change in base average is calculated and are summarized in the Table 2.

**Table 2** Calculation of base average, first variational term and second variational term for knee angular displacement using Average value based method.

Primary Sector	A Angular displacements corresponding to frame no 1 to 200	B Angular displacements corresponding to frame no 201 to 400	C Angular displacements corresponding to frame no 401 to 600
	Knee	Knee	Knee
Base Average Value for Right leg corresponding to angular displacement	167	170	168
First Variational Term for right leg corresponding to angular velocity	3.73	5.10	3.244
Second Variational Term for right leg corresponding to angular acceleration	12.9	11.188	13.204
Locking time corresponding to right leg	900 milli seconds		
Unlocking time corresponding to right leg	425 milli seconds		
Time between locking and unlocking	0.35 seconds		



**Fig 3.** Walking assistive device

The following three equations are formulated using the data collected in Table-2

$$167P_1 + 3.73P_2 + 12.9 P_3 = 3.6 \quad (6)$$

$$170P_1 + 5.1P_2 + 11.18888P_3 = 3.6 \quad (7)$$

$$168P_1 + 3.244 P_2 + 13.204P_3 = 3.6 \quad (8)$$

## 5. Formulation of Mathematical Equations

The tabulated knee angular displacement values are divided into three primary sectors viz., sector A, sector B and sector C. These primary sectors are then subdivided into secondary and tertiary sectors. Average value based method is applied to each sector and three equations are formulated using following approach

$$P_1*(B_{avg_A})+P_2*(\Delta B_{vg_A})+P_3*(\Delta^2 B_{avg_A}) = \text{distance covered corresponding to Primary Sector A}$$

The constants  $P_1$ ,  $P_2$  and  $P_3$  represents the physical parameters of the system,  $(\Delta B_{vg_A})$  is the first variational change that corresponds to secondary sector,  $\Delta^2 B_{vg_A}$  is the second variational change corresponds to tertiary sector. Similarly for Primary Sectors B and C

$$P_1*(B_{avg_B})+P_2*(\Delta B_{vg_B})+P_3*(\Delta^2 B_{avg_B}) = \text{distance covered corresponding to Primary Sector B}$$

$$P_1*(B_{avg_C})+P_2*(\Delta B_{vg_C})+P_3*(\Delta^2 B_{avg_C}) = \text{distance covered corresponding to Primary Sector C}$$

Thus the general equation for the characteristics of human movement can be formulated as

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  $P_1, P_2, P_3$ .

$$P_1*(\text{Base Avg}_X) + P_2*(\text{First change in Base Avg}_X)+P_3*(\text{Second change in Base Avg}_X) = \text{distance covered in Primary Sector X} \quad (5)$$

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-2. 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.

To make the cumulative 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  $i=0,1,2,\dots$ . This enables us to find the intermediate values.

## 6. Analysis and Discussion

Model for knee moment and angular displacement are developed using average value based method. By changing the values of  $N_1$ ,  $N_2$  and  $N_3$  in eqn (1),(2),(3), different values of moments at different angles can be obtained for the dynamic state. Similarly by changing the values of  $P_1$ ,  $P_2$ ,  $P_3$  in eqns (6),



(7) and (8) different values linear displacement is obtained for different angles of motion. By combining the equations, moment and angular displacement for different angles are obtained. The two models shows a positive relation ship to the average value based problem. The present walking assistive device with electrical actuation is bulky in size and weight. Since the dc motors are running on battery charge the size of the battery is a major concern for long distance locomotion with assistive device. Power source is always a major issue in any automated mechanism. Current and voltage are the other issues that affect the selection and maintenace of the power sources. Considering these factors, a different mechanism with low cost and widely available power source has to be selected for orthosis development. Here it is suggested that a pneumatic system is installed for the actuation purposes where the working fluid is the compressed air which is widely available.

## 7. Conclusion

High resolution camera was used to record the gait cycle positions and the angular displacement, angular velocities and angular accelerations has been measured and calculated. Using the data collected from the recorded video, an infinite series linear mathematical model has been developed and validated successfully. Forces and moments are calculated using newtons equations of motion. Knee moment is also calculated using average value based method and both methods show the similarity in results.

Practical realisation of the model developed has been performed by fabricating simple and cheap walking assistive device and its control techniques. The assistive device developed is simple, cheap and robust. Walking experiment is performed using fabricated walking assistive device and the gait movement were recorded using camera. The analysis results shows that a good match between natural human gait cycle and gait cycle with walking assistive device.

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