Development of lower body exoskeleton, mathematical modeling and video analysis of its prototype for obtaining customized joint actuation

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Abstract—Exoskeleton technology have shown its importance in various fields of application such as military, medical, industrial and commercial. But wide use of this technology is limited due high cost and Customized application according to user. If the exoskeleton has different gait cycle than unique natural gait cycle of user, it will lead to the injuries. Customization of exoskeleton gait cycle can overcome this challenge. Customized gait cycle according to user means control unit should provide output in form of position and torque in accordance to natural gait cycle of unique user. In this paper, A methodology is proposed and validated to obtain customized gait cycle for exoskeleton using video analysis and MATLAB simulation. Validation of Methodology is performed on normal human walking gait cycle. Video analysis performed in HALEX (Human Assistive Lower Limb Exoskeleton)is considered as basic method to conduct video analysis of gait cycle for unique user and data obtained from their experiment considered as base data for position vs time analysis. Later data obtained from video analysis is used as input data to obtain results fromMATLABSimscape-Simulink simulations using genetic algorithm. Above method is applied on biped robot to obtain results for normal human gait analysis. Simulations gives results in both position and torque wrt time. Torque values are compared with values obtained from mathematical model and position values are compared with values obtain from Video gait analysis. Validation of methodology gave satisfactory results and later suggested method can be used to obtain resulted torque and gait cycle for exoskeleton.

Keywords—Biped Robot, MATLAB-Simscape, genetic algorithm, exoskeleton, Normal Human Gait.

1. INTRODUCTION

From human to robot now back to human that is the trend in every industry. Yes, that’s right combination of human with robot overcomes many limitations of not only human but also robots. This is the primary need of robotic exoskeleton technology. Humans have limitations like risk of injury, fatigue due to repeated type of work and lack of strength for challenging task while robot’s high initial cost and cost of robot increases with increase in flexibility of control. But these limitations can be resolved if human dexterity of control and strength of machine is combined. This led to innovation and evolution of robotic exoskeleton in various fields of application.
In recent years Robotic Exoskeleton became a serious part of the Robotic industry. Application of exoskeleton is found in fields of military, medical, industrial, and civilian.

Exoskeleton technology has shown its importance in various fields of application such as military, medical, industrial, and commercial. But wide use of this technology is limited due to high cost and custom application according to user. For exoskeleton to obtain human like gait motion links must have predefined position with respect to (wrt) time and to obtained predefined position of links wrt actuator should provide predefined torque wrt time. In this paper, methodology is proposed and validated to obtain customized gait cycle for exoskeleton using video analysis and MATLAB simulation. Validation of Methodology is performed on normal human walking gait cycle. Video analysis performed in HALEX (Human Assistive Lower Limb Exoskeleton) is considered as basic method to conduct video analysis of gait cycle for unique user and data obtained from their experiment considered as base data for position vs time analysis. Later data obtained from video analysis is used as input data to obtain results from MATLAB Simscape-Simulink simulations using genetic algorithm.

Methodology to obtain customized gait pattern according to user have two steps. Step one is video analysis using video analysis software and step two is using data obtained from video analysis as input for genetic algorithm to perform simulation to obtain torque for actual gait pattern with exoskeleton.

To validate above methodology experiments are performed in four steps, first step is validation video analysis method of gait cycle using with normal gait pattern available. Second steps are generation of mathematical model of human body for walking to obtain torque required at various phases of walking. Third step is simulation of biped robot with gait cycle input from step one to obtain torque and position of joint wrt time. At the end comparison of results of simulation with video analysis to validate the gait cycle and mathematical model to validate torque required at various phases.

2. LITERATURE REVIEW

Need of customized Gait cycle for exoskeleton – skeleton have shown their versatile use in medical field for gait rehabilitation and augmentation to strength of paraplegic patients [4]. A driven gait orthosis (DGO) has been developed that can move the legs of a patient in a physiological way on the moving treadmill the orthosis is adjustable in size so different patients can use it. Actuators at the knee and hip joints are controlled by an edge controller. With the DGO the legs of patients with different degrees of paresis and spasticity could be trained [5]. Human Gait Cycle is dependent on various physical parameters of users like height, weight, gender, ages, lifestyle etc. and customization gait cycle for exoskeleton means obtaining gait cycle same as users not general gait cycle which one for all. The main concern was reaching the target angle within the allowable error quickly enough to track the trajectory (customized gait) during walking. If accurate control is not used, which would have aided in eliminating steady state error due to gravity and other factors because a control unit would have also worked against any sort of resistance from the patient? Because many paraplegic patients also have muscle spasticity, their muscles will fight the motion of the machine forcing the integrator term to wind up. Therefore, by overpowering the spasticity to move the joint, the machine could seriously injure the patient[3]. This type of injury can also affect normal user using exoskeleton as unique gait of user is altered by overpower exoskeleton To eliminate this risk, it is a need to develop a method to obtain customized gait from particular user. In this paper video analysis is used to study gait cycle of user and using MATLAB simulation to obtain torque related to gait cycle of user.

3. Step I : Study of Gait Cycle

Study of normal human gait using video analysis to obtain angle position vs time graph throughout the normal gait cycle
Human walking is common yet most important form of human movement. Gait analysis measures, analyze and assesses the bio mechanical features that are associated with the walking task. Therefore gait analyses have application all considerable fields of locomotion.

Dartfish is a video solution provider from Switzerland. Dartfish provides online and offline platform to view, analyze and edit video for individuals and corporate.

The variation of joint angles of subject (age 21) walking on a treadmill were recorded using a video camera fitted on a stand of three legs in a sagittal plane while subject walked on a motorized treadmill one, the treadmill is often used in exoskeleton development programs because it allows standards and controlled conditions and it needs small space. These video was analyzed for joint angles on Dartfish Pro, video analysis software.

Analysis of Hip Angle and knee angle is performed on 25 frames per second settings.

The basic requirement video analysis method to be used is that it should give unique gait cycle for unique user which may different from average gait cycle mass users. This step is very important step to obtain customized output gait cycle for exoskeleton according users. Such type of video analysis can provide gait cycle accommodating different physical parameters like height, weight, gender, age etc. this analysis is performed on Dartfish sports analysis software, Fig. 6 and Fig. 8 show measurement of angle of knee and Hip wrt time on treadmill setup. Fig. 7 and Fig. 9 show the result with highlighted single cycle in Gait.

![Fig. 1 Measurement of angle of knee wrt time](image-url)
Fig. 2 Results of Knee angle (Single cycle in Gait is highlighted by rectangle) [1]

From Fig. 2 shows that single cycle is highlighted by rectangle and it is repeating the same pattern wrt time. Therefore angular position at knee joint angle ranges from 115 to 180 degrees i.e. 65 degrees.

Fig. 3 Measurement of angle of hip wrt time [1]
Fig. 4 Results of Hip angle (Single cycle in Gait is highlighted by rectangle) [1]

From Fig. 4 shows that single cycle is highlighted by rectangle and it is repeating the same pattern wrt time. Therefore angular position at hip joint angle ranges from 160 to 200 degrees i.e. 40 degrees.

Fig. 5 The CGA Trajectories Used For the hip and knee angle shows the range of the joint angle used to achieve walking. [3]

Fig. 5 is reference gait cycle for average user. This average normal human gait cycle is reference to validate video analysis process to obtain unique gait for unique user. From fig. 5 shows that both knee and hip angular position are shown single graph. Due to different reference angle for measurement of angular position graphs are inverted and starts near zero degree. Therefore angular position at knee joint ranges from 0 to 55 degrees i.e. 55 degrees and similarly at hip joint ranges from -22 to 19 degrees i.e. 41 degrees.

4. Step II : Calculations

Calculation of torque required for human walking at various stages of normal human gait using Mathematical Model

To generate mathematical model of human body to obtain torque required at various phases of gait following data of human body weight and height is used from Table 1 and Table 2 respectively.
Table. 1 Human Body Weight Distribution [2]

| Segment         | Average % | Average (kg) |
|-----------------|-----------|--------------|
| Total (M)       | 100       | 80           |
| Head (Mh)       | 6.81      | 5.45         |
| Trunk (Mt)      | 43.02     | 34.4         |
| Total Arm (Ma)  | 4.715     | 3.77         |
| Upper Arm       | 2.63      | 2.10         |
| Forearm         | 1.5       | 1.2          |
| Hand            | 0.585     | 0.47         |
| Total Leg       | 20.37     | 11.58        |
| Thigh (Mth)     | 14.47     | 11.58        |
| Shank (Msh)     | 4.57      | 3.66         |
| Foot (Mfo)      | 1.33      | 1.06         |

Table. 2 Human Body Height Distributions

| Segment   | Average % | Average (cm) |
|-----------|-----------|--------------|
| Total (H) | 100       | 180          |
| Total Leg | 56.2      | 101.16       |
| Thigh (L1)| 28.1      | 50.58        |
| Shank (L2)| 28.1      | 50.58        |
| Foot (L3) | 14.05     | 25.29        |
| Total Arm | 39.3      | 70.74        |
| Head      | 15.7      | 28.26        |
| Torso     | 28.1      | 50.58        |

For generation of mathematical model for normal human walking subject of height 180 cm and weight 80kg is considered. From video analysis it was noted that average gait cycle time for normal human walking is 1 second and stride length is 60 cm. Torque require at crucial phases in gait cycle are calculated. It was observed in modelling that torque required at ankle throughout gait cycle in negligible.

Fig. 6 shows stance and swing phases of normal gait cycle of human along with 8 sub phases. To obtain torque at these sub phases following formulas are derived.

Fig. 6 Phases of Normal Human Gait Cycle [6]
For stance phase - 

Human walking requires less torque than maximum torque capacity human joint. Human walking is only possible if sufficient friction is available between ground and human foot. Thus, friction plays very crucial role in calculation of torque phase. In stance phase both horizontal and vertical forces are acting on joints.

Average step length = 60 cm = 0.6 m 
average duration of one gait cycle = 1 sec 
\[ s = u \cdot t + 0.5 \cdot a \cdot t^2 \]
\[ 0.6 = 0 + 0.5 \cdot a \cdot 1 \cdot 1 \]
\[ a = 1.2 \text{ m/s}^2 \]

Total mass of human body = \( M = 80 \text{ Kg} \)

F = \( M \cdot a = 80 \cdot 1.2 = 96 \text{ N} \)

Therefore Inertia force = \( I = F = 96 \text{ N} \)

Friction coefficient = \( u = 0.5 \)

Normal force = \( N = M \cdot g = 80 \cdot 9.81 = 784.8 \text{ N} \)

Maximum Friction force = \( F_{mc} = N \cdot u = 0.5 \cdot 784.8 = 392 \text{ N} \)

\( F_c = \) actual friction force required.

Force required for human walking obtain from ground i.e. friction force. Therefore required friction force \( (F_c) \) should be less maximum available friction force.

After calculating torque required at various sub phases, mid stance is the critical sub phase with highest torque required within stance phase.

![](image)

**Fig. 7 mid stance sub phase of Normal Human Gait Cycle**

\( F_{rc} = \) reaction of friction on human body = \( F_c \)

\( M_{rc} = \) reaction moment of \( F_c \) at knee 

\( M_k = \) torque required at knee b

\( M_{rc} = \) reaction moment of \( F_c \) at knee

\( M_k = \) torque required at knee by actuator

\( M_{rk} = \) reaction moment due to torque at knee at hip

\( F = \) force required for walking at defined speed

\( M_h = F \cdot 0.3 \text{ N m} = 96 \cdot 0.3 = 28.8 \text{ N m} \)

\( M_k = M_h + F \cdot 0.8 = 28.8 + 96 \cdot 0.8 = 105.6 \text{ N m} \)

\( M_k = M_{rc} = F_c \cdot 0.5 = 105.6 \text{ N m} \)

\( F_{rc} = 212 \text{ N} \)

\( F_{rc} = F_c = 212 < F_{mc} = 392 \text{ N} \)

Thus,

\( M_h = 28.8 \text{ N m} \) \( \) (at hip)

\( M_k = 105.6 \text{ N m} \) \( \) (at Knee)
For swing phase -
For swing phase legs perform pendulum free swing motion so equation requires calculating torque for swing phase are different from stance phase.

After calculating torque required at various sub phases, terminal swing is the critical phase with highest torque required within swing phase.

![Diagram of terminal swing sub phase of Normal Human Gait Cycle](image)

Moment equation at hip
\[ Mo_1 = L_1 \times 0.5 \times \sin(30) \times M_{th} \times g + M_{sh} \times g \times [L_1 + L_2 \times 0.5] \times \sin(30) + M_{fo} \times g \times [L_1 \times \sin(30) + L_3 \times \cos(30) \times 0.5] \]
\[ Mo_1 = 50.58 \times 0.5 \times 0.5 \times 11.58 \times 9.81 + 3.66 \times 9.81 \times [50.58 + 50.58 \times 0.5] \times 0.5 + 1.06 \times 9.81 \times [(50.58 + 50.58) \times 0.5 + 25.29 \times 0.86 \times 0.5] \]
\[ Mo_1 = 1436.5 + 1362 + 639 \text{ N cm} \]
\[ Mo_1 = 34.4 \text{ N m} \]

Moment equation at Knee
Foot is not in contact with ground normal force and friction forces are not considered in moment calculation.
\[ Mo_2 = M_{sh} \times g \times L_2 \times 0.5 \times \sin(30) + M_{fo} \times g \times [L_2 \times \sin(30) + L_3 \times 0.5 \times \cos(30)] \]
\[ Mo_2 = 454 + 376 \text{ N cm} \]
\[ Mo_2 = 8.3 \text{ N m} \]

Thus,
\[ M_h = 34.4 \text{ N m (at hip)} \]
\[ M_k = 8.3 \text{ N m (at Knee)} \]

5. BIPED ROBOT SYSTEM

This is simple stick and brick body version of Biped robot walker system. MATLAB Simulation using Simscape is performed on this system to compare results with video analysis and calculated torque. Genetic algorithm with 100 generation and 100 population size is used i.e. total 10000 experiments are performed on this biped robot system to learn human like walking. For genetic algorithm converge on results according to initial condition provided at the beginning of the experiments [7].

For Biped robot system,
Length of thigh is 40 cm.
Length of shank is 40 cm.
Density is 1000 kg/m$^3$ (Human body density is 980 kg/m$^3$) 
Total weight is 5.588 kg.

Fig. 9 Biped Robot System using simple Stick and brick model [7].

For normal human walking 6 DOF are required for human i.e. Ankle Roll, Ankle pitch, Knee, Hip Roll, Hip Pitch and Hip Yaw. Above biped robot model have same DOF as normal human.

6. RESULTS & DISCUSSION

Results of MATLAB Simulation of Biped Robot.

 a. Hip roll

Fig. 10 Joint angle and joint torque wrt time for Hip roll

From fig. 10 shows the angular position and torque required at hip roll. In angle vs time it is observed single cycle in gait as highlighted in rectangle and variation of total angle throughout the cycle is -0.15 rad to 0 rad i.e.range is 8.6 degrees. Range and Max joint torque is 0 Nm to 20 Nm and 20 Nm respectively.
b. Hip pitch

Fig. 11 Joint angle and joint torque wrt time for Hip pitch

From fig. 11 shows the angular position and torque required at hip pitch. In angle vs time it is observed single cycle in gait as highlighted in rectangle and variation of total angle throughout the cycle is 0.3 rad to 0.8 rad i.e.range is 28.6 degrees. Range and Max joint torque is -15 Nm to 20 Nm and 20 Nm respectively.

c. Hip Yaw

Fig. 12 Joint angle and joint torque wrt time for hip yaw
From fig. 12 shows the angular position and torque required at hip yaw. In angle vs time it is observed that joint angle range and torque required is negligible. Therefore contribution of hip yaw in gait cycle torque requires for normal human walking is negligible.

d. Knee

Fig. 13 Joint angle and joint torque wrt time for Knee

From fig. 13 shows the angular position and torque required at Knee joint. In angle vs time it is observed single cycle in gait as highlighted in rectangle and variation of total angle throughout the cycle is -1 rad to -1.5 rad i.e. range is 28.6 degrees. Range and Max joint torque is 0 Nm to 45 Nm and 45 Nm respectively.

e. Ankle Pitch

Fig. 14 Joint angle and joint torque wrt time for Ankle pitch
From fig. 14 shows angular position and torque required at ankle pitch. In angle vs time it is observed single cycle in gait as highlighted in rectangle and variation of total angle throughout the cycle is 0.4 rad to 0.8 rad i.e. range is 22.9 degrees. Range and Max joint torque is -10 Nm to 20 Nm and 20 Nm respectively.

f. Ankle Roll

From fig. 15 shows angular position and torque required at ankle roll. In angle vs time it is observed single cycle in gait as highlighted in rectangle and variation of total angle throughout the cycle is 0 rad to 0.15 rad i.e. range is 8.6 degrees. Range and Max joint torque is -10 Nm to 20 Nm and 20 Nm respectively.

7. SUMMARY OF RESULTS

1. MATLAB simulation using simscape and genetic algorithm is able to teach biped robot to walk human like gait cycle.

2. Results obtain from video analysis of human gait using treadmill setup (Fig. 2 and Fig. 4) matches with reference gait cycle (Fig. 5). From Hip Angle of gait cycle using video analysis matches exactly to reference gait in terms of pattern and range. Also Knee angle of gait cycle using video analysis matches the pattern only inverted (due different reference angle for measurement) and range is 10 degrees less than reference gait cycle.

3. Gait cycle can be different for different person according there physical parameters like weight, height, gender, age etc. So gait cycle obtain from video analysis is different from overall average gait cycle for unique test subject.

4. Gait cycle obtained from biped robot system for hip pitch angle matches for pattern with gait of video analysis gait cycle. But range of angle is 12 degrees smaller

5. Gait cycle obtained from biped robot system for knee angle matches for initial and terminal phases of gait cycle to gait cycle obtain from video analysis but biped robot gait is flattened for mid swing phase. Thus range of angle varies for almost 30 degrees.

6. From Mathematical modeling of human walking maximum torque is required at knee during mid stance during stance phase is 105.6 Nm. Similarly Maximum torque required for biped robot system is at mid stance phase and equal to 45 Nm.
7. It can be observed from mathematical modeling and biped robot simulation that Torque required at hip joint is less than knee joint throughout the gait cycle.
8. from mathematical modeling it was calculated Torque at required at ankle is negligible but simulation shown torque required at ankle is significant.

8. CONCLUSIONS

1. Results obtain from video analysis and simulation of biped robot for position vs time graph i.e. Gait cycle are as following.

   For knee –
   From Fig. 2 and Fig. 13 we can observe that range of gait cycle of Video analysis and biped robot simulation is 65 deg and 28.6 degree. Pattern of simulated results matches with video analysis 50 %.

   For hip –
   From Fig. 4 and Fig. 11 we can observe that range of gait cycle of Video analysis and biped robot simulation is 40 deg and 28.6 degree. Pattern of simulated results matches with video analysis 70 %.

From above result we can conclude that gait cycle obtained is fairly matching for unique user.

2. Results obtain from Mathematical Modeling and simulation of biped robot for Torque vs time graph are as following.

   For knee –
   From mathematical modeling max torque in Stance and swing phase are 105.6 Nm and 8.3 Nm respectively and from simulation of biped robot in stance and swing phase are 50 Nm and negligible.

   For hip –
   From mathematical modeling max torque in Stance and swing phase are 28.8 Nm and 34.4 Nm respectively and from simulation of biped robot in stance and swing phase is almost equal and around 20 Nm.

From above result we can conclude that Torque required for mathematical model and simulation follows pattern.

3. MATLAB Simulation using Simscape with genetic algorithm can be used to teach human like walking to Model of human body with and without exoskeleton.
4. Torque results obtain from simulation are in correspondence to torque results obtain from mathematical modeling of normal human walking.
5. Overall above methodology to generate customized gait for exoskeleton using Video analysis of test subject and MATLAB simulation to generate torque require at joint actuator can be used.

Still there scope in refining proposed methodology, above method can be used on different exoskeletons to further check out this method to obtain customized gait cycle for exoskeleton. Simulation results can be improved by using Bio Mechanical simulation of human body i.e. more human like biped robot instead simple stick and brick diagram so that actual human like weight distribution in robot can be obtain. Optimization results can be improved by designing more detail cost function and allowing more iteration to learn.
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