

Walking simulation model of lower limb exoskeleton robot design

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ABSTRACT – Since 1960s, the development of exoskeleton robots have been advancing in the applications such as load carrying, walking endurance, physical assistance and rehabilitation therapy. Rehabilitation therapy in itself is related to walking ability restoration; especially for the elder people. A survey by The United Nations in 2017 revealed increase trend in the number of ageing population. Due to ageing, it may cause weakened limbs, lower limb injuries or disabilities resulting in walking impairment. Elder people suffering from walking impairment will need to undergo walking therapy to recover walking ability. A walking rehabilitation exoskeleton robot can be used for such patients to undergo the therapy by wearing it on their lower body. A lower limb exoskeleton effectiveness for gait recovery assessment in the design stage is not truly explored yet. This can be done by obtaining the simulation model of the lower limb exoskeleton robot structure from its CAD design. The gait pattern tracking response performance of the exoskeleton design to given inputs can then be observed. The lower limb exoskeleton structure is designed using Autodesk Inventor and then imported into SimMechanics. A block diagram of the exoskeleton model is generated, whereby the model is simulated and its response is observed. Given mathematical expression and experimental data inputs, the exoskeleton model with control system is able to track given joint trajectory inputs. The lower limb exoskeleton model shows that the response of its joints to the inputs can replicate human joints behavior during walking for any given stimulus inputs.

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INTRODUCTION

Exoskeleton robot or commonly known as exoskeleton is a powered wearable anthropomorphic robotic suit [1-3]. It can be worn either on the whole or parts of the human body. Its purpose is to augment, assist, restore human limb function or for rehabilitation therapy depending on applications. The exoskeleton can be categorized by body parts [2] and also by medical and non-medical applications [4]. The lower body, lower extremity or widely known as lower limb exoskeleton robot is designed to be worn parallelly to the lower part of human body to cater for walking function.

For many years, universities and research institutions in collaboration with company researchers have been trying to develop exoskeleton robots that can help human to perform tasks beyond his limit or restore human disabilities. These include the research developments on full body, upper limb, lower limb and modular exoskeletons. The lower limb exoskeletons have been developed for many purposes such as in load carrying [5], guided walking trajectory [6], walking endurance [7, 8], walking assistance [9] and walking rehabilitation therapy [10-18]. Mostly the focus are on increasing or restoring human walking ability. In those exoskeletons, human provides the intelligent control system and the exoskeleton actuators provide most of the strength necessary for walking. Coupled together, both human and exoskeleton form the overall concept of this lower limb exoskeleton. Some of the widely known exoskeletons are BLEEX [19] for augmentation in load carrying while walking, HAL [20] for walking assistance and Lokomat [21] for walking rehabilitation therapy.

Around 1965, General Electric developed Hardiman [22], a full large body exoskeleton for strength augmentation of the arms and legs. In 2005 Zoss, Kazerooni and Chu [23] from the University College of Berkeley developed BLEEX, a lower limb exoskeleton robot. It was considered as the first energetically autonomous exoskeleton robot. Its anthropomorphic design made it wearable on human lower body part. Due to that, the wearer is made capable of carrying heavy payload while providing the wearer walking endurance for long distance at the same time. Later in 2009, Kazerooni team in Berkeley Robotics together with Ekso Bionics developed HULC, a hydraulic powered exoskeleton enabling soldiers to walk longer while carrying payloads. With regard to this work, Kazerooni has been dubbed as the “father of modern exoskeleton”. Following this, researches in the development of exoskeletons around the world have been advancing.

Apart from augmentation, the exoskeleton also can be used for support and assist. Ikeuchi et al. [24] from Honda created a bodyweight support assist in 2009. It was a powered exoskeleton that worked to reduce user felt weight during walking by distributing and diverting the user weight to the support structure. In 2014, a group of Honda researchers created Honda Stride Management Assist to boost user hip motion during walking. It has been tested on Parkinson disease patients and proven to increase the step length of the patients [25]. These exoskeletons have been used to assist and strengthen human performance. Human movements are detected by EMG, force or position sensors as feedback to the exoskeleton in determining the assist and support needed. Lovrenovic and Doumit [26] describe the assistive exoskeleton as leg joints inserted with energy to provide walking assistance.

Rehabilitation exoskeletons on the other hand provide person undergoing therapy assistance to follow therapy session specified by a therapist with minimum observation. Some researches on the rehabilitation exoskeletons and devices include Zoss, Kazerooni and Chu [23] BLEEX (Berkeley Exoskeleton), Kawamoto et al. [20] HAL-3 (Hybrid Assistive Leg), Pratt, et al. [27] Roboknee, Walsh, Endo and Herr [28] quasi-passive exoskeleton and Rewalk by Zeilig et al. [29]. Those devices work by providing flexion and extension torques at hip joint to walk over extended periods of time with minimal fatigue while carrying heavy loads [26] or opposing muscles impedance and joint resistance during therapy [30]. Exoskeletons like BLEEX and HAL-5 can carry extra payload besides their own weight while Rewalk aids paraplegics to regain their upright mobility. These exoskeletons can also be used for portable or overground rehabilitation therapy.

When a wearer applies or dons an exoskeleton suit, mechanical connections or couplings are established between the wearer and the exoskeleton at the torso and the feet. In addition, the wearer and the exoskeleton may have compliant or periodic contact elsewhere. The structure design should be fit or adjustable according to human anthropometry. One of the essential objectives in the design is to allow the robot joint angles or joint positions to be able to accommodate the force and motion of human joints as much as possible. For normal exoskeleton according to Bogue [31], human must provide more power than the exoskeleton itself for the exoskeleton to be considered as safe. The conditions for good safety have been discussed by Sen [32] and Yu et al. [33]. To avoid injuries, the exoskeleton structure must be light, safe and comfortable to be used for elder and ageing people.

A survey by The United Nations in 2017 found that by 2050, the ageing population will account to about 23% of global population [34]. One of the traits attributed to the ageing population is the reduced ability to walk or walking impairment. Walking gait impairment mostly happens as a result of damage to the human central nervous system (CNS) [35] which consists of the brain and spinal cord. Injuries to either the brain or the spinal cord to the parts that control the nervous system to the lower limb may cause difficulty in walking. This results in gait disorder. In severe injuries, the lower limb may become paralyzed and the sufferer cannot walk anymore. To restore the walking ability for the person with incomplete paralysis, walking therapy as a rehabilitation process is required. With the advancement in robotic technology nowadays, robotic therapy has been used alongside with the minimum number of therapists required to perform the walking rehabilitation therapy [18, 21].

Many researchers around the world focus their interest in studying the use of exoskeleton for restoration of walking gait impairment in rehabilitation therapy, post stroke recovery [36] and post surgery therapy [37]. In doing so, they have to study human mechanics of walking such as the study made by Chen et al. for designing the exoskeleton [38] and [39]. These include the various human walking movements which involve the use of lower limbs such as the pelvis, thigh, leg and foot that links to the hip, knee and ankle joints according to Bo [40]. On the other hand, human walking movement using smaller scale humanoid robot has been studied by Shah et al. [41]. Miao et al. [42] studied four different types of movement with different modes in order to find the particular action state for walking, running, jumping and squatting suitable with use of exoskeleton for therapy. All these factors determine the way an exoskeleton structure for walking rehabilitation is designed.

There are many lower limb exoskeleton designs being produced and many designs have been patented throughout the world. Cohen overviewed the exoskeleton patent landscape in 2017 and found the trend of increasing growth in the number of patent applications [43] for exoskeletons. According to a survey in US patent by Lai and Li in 2015 [44], the lower limb exoskeleton design evolved with the advancement of technologies during the last four decades. Jiang et al. in 2017 reviewed some patents and suggested that if the exoskeleton size, weight and power issues can be solved at the same time, the exoskeleton will become more consistent with human body [45]. As the technology for exoskeleton becoming more sophisticated, so as the cost for developing the exoskeleton. The development cost is very high from the design stage up to a full working prototype. Exoskeleton structure fabrication forms the bulk of the prototyping cost somehow without the knowledge of the exoskeleton prototype efficacy. It is very costly to test the response of the exoskeleton control system after the exoskeleton has been fabricated.

Therefore, there must be a method whereby the exoskeleton structural design can be utilized in modelling a control system to be used to control the actual exoskeleton prototype after it has been fabricated. The exoskeleton structural design can normally be drawn in Computer aided design (CAD) software such as the widely used SolidWorks and Autodesk Inventor. After the exoskeleton has been designed, the designs can either been directly fabricated or simulated prior to fabrication. One of the methods to simulate the design is to use SimMechanics; a toolbox in MATLAB Simulink [46]. Some non-exoskeleton designs that have utilized the CAD designs simulation in SimMechanics are the laboratory truck crane by Cekus [47] and 6-degrees of freedom robot manipulator by Fedák, Ďurovský and Ůveges [48]. Examples on some exoskeleton designs simulation are Li et al. [49] with SimMechanics simulation, and Shaari, Isa and Jun [50] which used SolidWorks alone while Autodesk Inventor used by Olinski, Lewandowski and Gronowicz [51] but are not simulated in SimMechanics. Liu et al. have designed the exoskeleton for medical disabled and used ADAMS and MATLAB for simulation. Only few of the lower limb exoskeleton designs have been simulated utilizing SimMechanics.

Due to these reasons, this study aims to develop a walking simulation model of a lower limb exoskeleton design in SimMechanics. The lower limb exoskeleton design used is based on the work of Sapiee et al. [52], created in Autodesk Inventor. This paper proposes simulating the walking kinematics of a lower limb exoskeleton design for walking rehabilitation. The simulation of the exoskeleton design is supported with the application of Matlab SimMechanics First Generation where the design is converted into a MATLAB Simulink model using SimMechanics. SimMechanics is a block based mechanics tools integrated with the existing Simulink library and combined with the power of MATLAB. Through this integration, the design model together added with its own control system can be simulated while its responses can be analyzed. The cost of fabricating the actual structure can be reduced before coming out with an exoskeleton prototype.

METHODS AND MATERIALS

The lower limb exoskeleton design is modelled directly into a block diagram. A control system assigned to the joints in the block diagram. The model is simulated to given inputs to see its kinematics response behaviour. The response of the joints in the design should replicate human joints behavior.

The Lower Limb Exoskeleton

The process started with the lower limb exoskeleton designed with Autodesk Inventor Professional 2016 software, producing a structure as illustrated in Figure 1. The exoskeleton design resembles the human lower body part consisting of two legs connected at waist. Each leg has three joints at the hip, knee and ankle. In the original design, the joints has no actuator and gear but in the simulation model of the block diagram, an actuator block is introduced to each joint to move the joints to produce a forward walking gait.

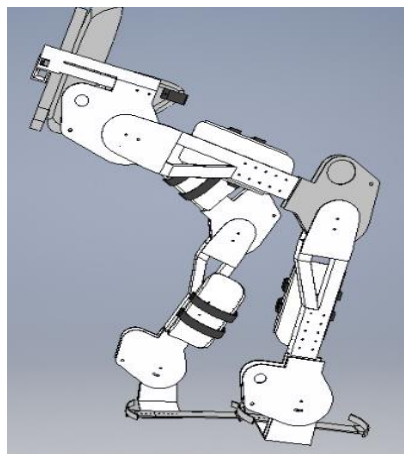


Figure 1. Exoskeleton design

Lower Limb Exoskeleton Design Properties

The structure of the lower limb exoskeleton is designed in Autodesk Inventor software to with specific design requirements. The materials selected in the design are Aluminum alloy 6063 hollow rod with density of 2.69 g/cm^3 for the links and Aluminum alloy 1100-H14 with density of 2.8 g/cm^3 for the joints and foot plates. The overall weight of the exoskeleton considering the materials used in the design has been estimated by the software at 11.9 kg; excluding the electrical circuit and actuators. There is only one degree of freedom (DOF) considered each at hip, knee and ankle joints. These are the DOFs required for forward movement in sagittal plane. The hip and knee joints having flexion and extension movement while dorsiflexion and plantarflexion movement at ankle joint. The sum of maximum flexion and maximum extension angles in clockwise and anti-clockwise directions at each joint gives the range of motion (ROM). The ROM of each joint on the exoskeleton design should match with the ROM of human joints. The designed exoskeleton structure should be easily donned and doffed by the wearer.

The exoskeleton structure is designed for 6DOF movement in sagittal plane with 3DOF in each leg left and right legs for hip (θ_h), knee (θ_k) and ankle (θ_a) joints. The joint angle definitions for the lower body parts for a single leg is as depicted in Figure 2, based on Winter's limb segment angles [53] and somewhat similar to the direction definition in [54]. The 6DOF are the minimum requirement in order for the robot to move forward, similar to human while normal human walking gait required 12DOF. The design is drawn for use by patient with height between 157 to 165 cm according to Winter's height to body proportion [53]. The lower limb exoskeleton structure must be able to be worn by patient with safety and stability. Instead of fabricating the exoskeleton design and develop the hardware, the design is modelled to

analyze its response through the use of MATLAB similar to Ali et al. [55] in using MATLAB with PID controller in their work.

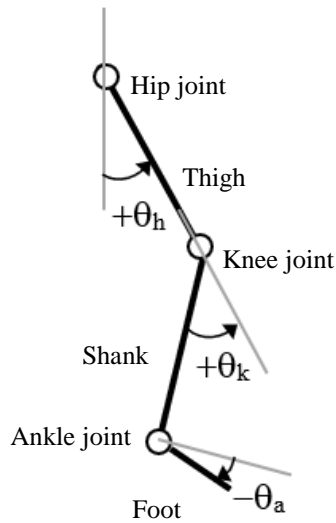


Figure 2. Joint angle definitions

From Design to Block Diagram

The original exoskeleton design in Autodesk Inventor is saved as CAD files consisting of part files (ipt file) and an assembly file (iam file). From there, the design is later imported into SimMechanics First Generation under MATLAB version R2015a. By option, the design can also be exported to SimMechanics Second Generation but in this study, the former is used. Once exported, a design data in xml format (xml file) is created in the same directory of the CAD files. At this point, the xml file cannot be read by MATLAB. The file needs to be called by certain MATLAB function. The following are the commands that need to be entered in MATLAB command window (italicized font refers to name of directory and file).

```
MATLAB commands:
>> addpath('directory containing filename.xml')
>> mech_import ('filename.xml')
```

Upon entering the commands on the xml file imported from Autodesk Inventor, external graphic stereolithography files (stl files) are created automatically by MATLAB. They contain parts geometric information from the original Autodesk Inventor part files (ipt files). Simultaneously, a Simulink viewer is opened showing a generated SimMechanics block diagram model of the exported lower limb exoskeleton design in MATLAB. It consists of several blocks representing the exoskeleton is as shown in Figure 3. When the block diagram is simulated, MATLAB utilizes the stl files to visualize the mechanical model as originally drawn in Autodesk Inventor. The block diagram can later be saved as a Simulink model (slx file).

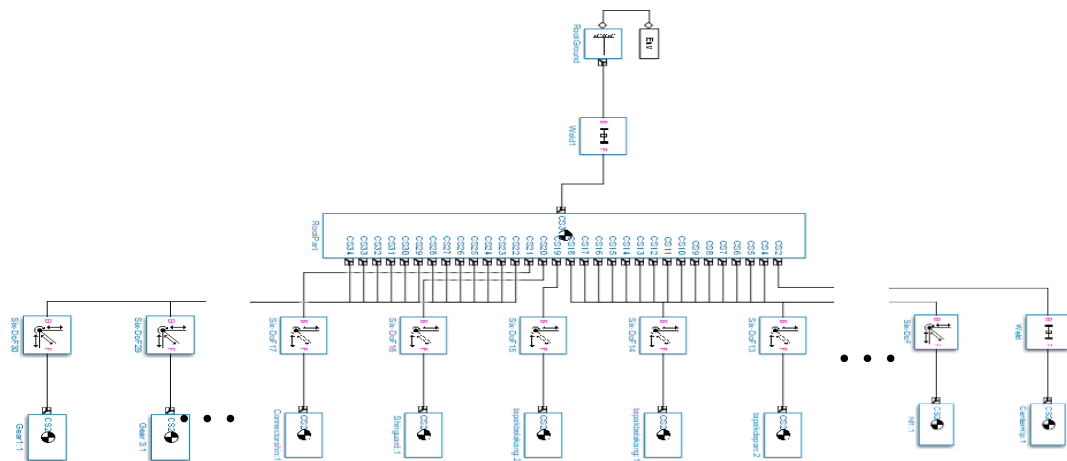


Figure 3. Before modification. Every part is connected to rootpart via Six-DoFs block

Before the block diagram is simulated, it must be ensured that the stl files are stored in the path which is recognized and accessible by MATLAB. It is important to add the path in the MATLAB command so that the stl files which hold the original drawings and design informations from the original CAD software can be read by MATLAB.

MATLAB command:
 >> addpath('directory of the stl files')

Normally, the path of the stl files is the same path containing the xml file. The SimMechanics block diagram model in Figure 3 must be rearranged and modified to resemble the shape of the lower limb exoskeleton design with right leg and left leg being attached to center of hip. After rearrangement, all joints between every body block need to be modified and changed to either weld block or revolute block. The resulting block diagram with new arrangement after modification and rearrangement is shown in Figure 4. The block diagram illustrates the building blocks that form the waist, right leg and left leg. As the exoskeleton is designed to have DOFs only in sagittal plane, all joints have only revolute movement in form of extension or flexion. The simulation can be run after each joint has been given input in the form of joint position or joint angle.

In Figure 5, the block diagram from Figure 4 is shown for left leg with individual control added system to hip, knee and ankle joints. The individual control system consists of a PID controller to each joint. The exoskeleton has been designed beforehand with 6DOF, 3DOF on each leg with every joint in each leg having only 1DOF. So, in order to have all DOFs in sagittal plane only, the Six-DoFs SimMechanics block is changed to revolute block. The revolute block is then connected to the joint actuator and joint sensor blocks. The joint actuator functions as actuator to actuate each joint and it receives the input from external source while the joint sensor reads the joint output in terms of position angle, velocity and torque. Figure 6 is a magnified view of the control system for an individual joint taken from Figure 5.

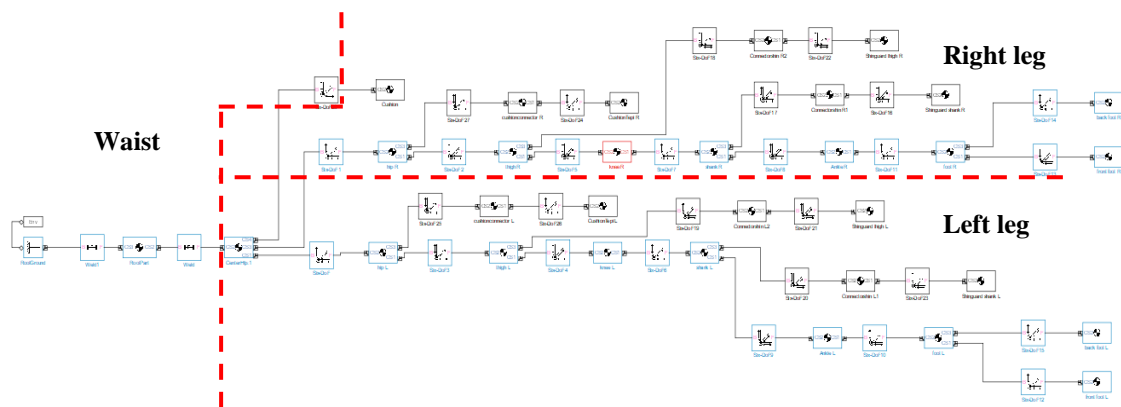


Figure 4. Rearranged and modified with only joints connected to Six-DoFs block

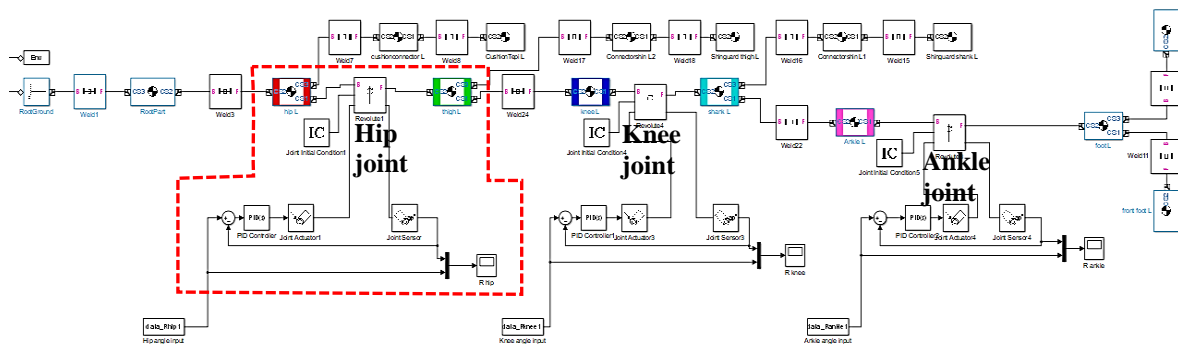


Figure 5. Exoskeleton left leg model with individual control to hip, knee and ankle joints

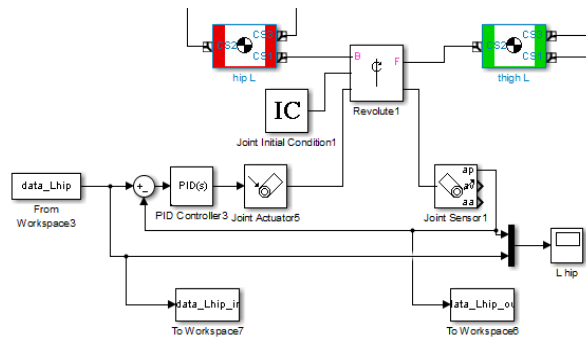


Figure 6. Magnified view of a joint control system

The process flow to develop a walking simulation model of an exoskeleton design is summarized in Figure 7. Running the simulation compiles the block diagram and displays the animated lower limb exoskeleton robot design according to the time duration of the input. The animated design is displayed almost exactly as it is designed in the Autodesk Inventor software. Figure 8 shows the simulated design as it appears in different environments. Figure 8a) shows the exoskeleton design as appeared in SimMechanics Visualization Window while Figure 8b) shows the actual design in Autodesk Inventor. Joints are marked to show similarities in joint locations in both as they appear to be in somewhat similar design.

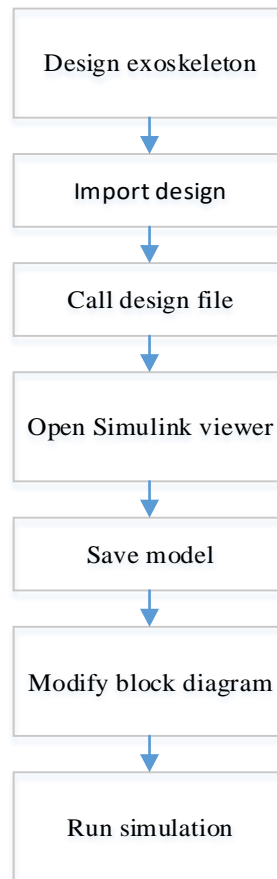


Figure 7. Design simulation process flow

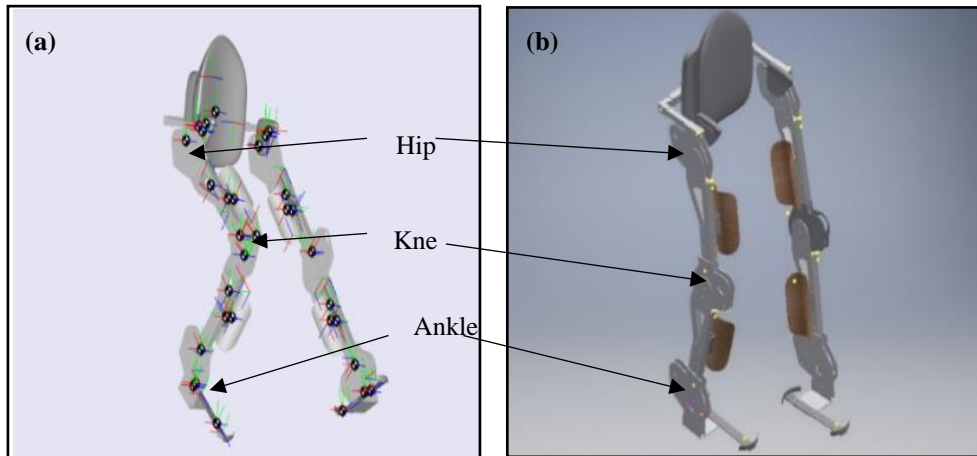


Figure 8. Exoskeleton joint positions: (a) SimMechanics simulation and (b) actual CAD design

RESULTS AND DISCUSSION

The following simulations are performed on the exoskeleton model block diagram by giving sinusoidal, mathematical and numerical inputs. The inputs in the form of joint position angle is given as reference to each joint in the control system. The following results are shown only for the left part of the exoskeleton leg. The graphs are plotted as joint position response for hip, knee and ankle joint positions over time.

Simulation with Sinusoidal Input

Human walking is a repetitive process. So, as the human walking gait to be imitated by the exoskeleton is periodic, the exoskeleton model is tested with sinusoidal inputs [56] similarly to the right and left legs with different position amplitudes to both legs hip, knee and ankle joints. The responses are shown in Figure 9 for single leg where the blue line outputs seem to have some tracking of the red line inputs except for some deviations at the amplitudes.

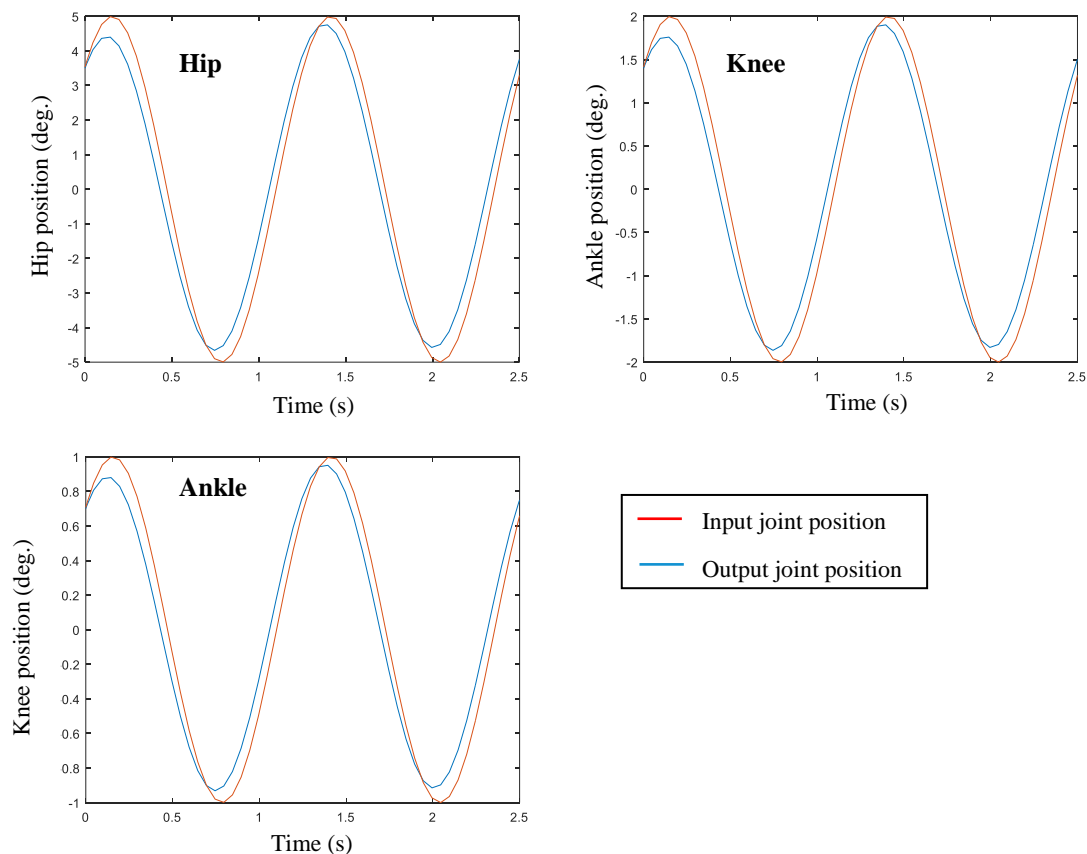


Figure 9. Response graphs of the lower limb exoskeleton robot joints showing output to input tracking

Simulation With Polynomial Expression Input

Mathematical model can be used as input to the joints [57]. A quantic polynomial in general form as depicted in Eq. (1) from Mohammed et. al. [58] is taken as input to each joint of the exoskeleton model. A gait cycle is divided into several subphases and the responses from each subphase are plotted for the whole gait cycle. The coefficients to the quantic polynomial expression [58] are used according to the type of joints resulting in three joint position (θ) equations for hip, knee and ankle positions. The responses are shown in Figure 10 with bold blue line as input and light blue line as output.

$$\theta(t) = a_0 + a_1t + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5 \tag{11}$$

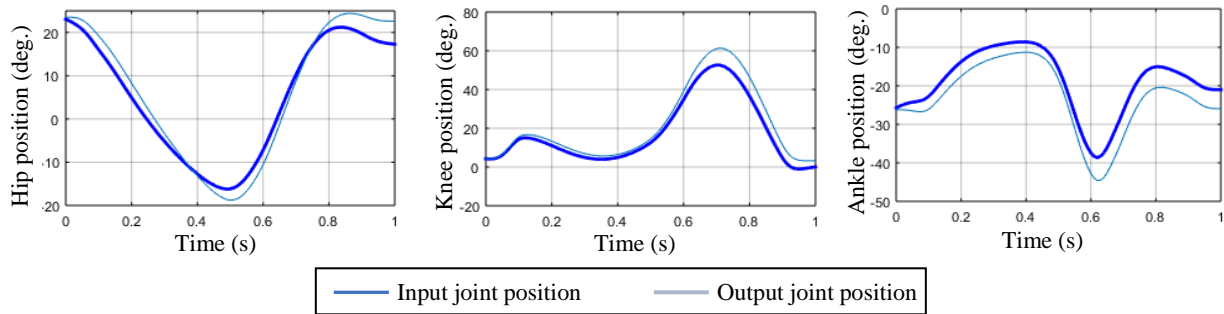


Figure 10. Response based on mathematical input

Simulation With Gait Data Input

The exoskeleton model is next simulated by feeding the joint inputs with numerical gait data in time and joint positions from Semwal and Nandi [59] as reference trajectories to each joint, Figure 11 shows the response whereby the bold blue lines are the numerical inputs and light blue lines are the output.

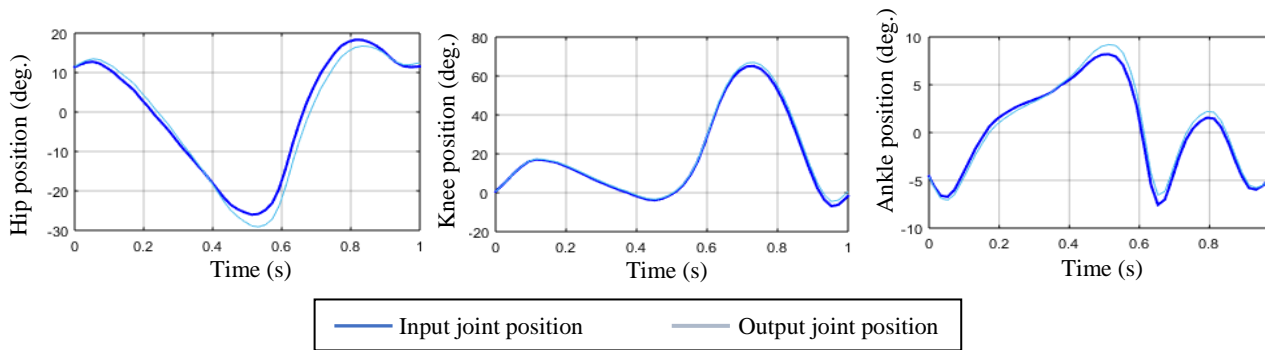


Figure 11. Response based on numerical data

The results show that the exoskeleton structure modelled as SimMechanics block diagram can be actuated at each joint. By using the sensor block, it can be added as feedback from the output to form a control system which can later control the output for better curve tracking. In addition to this, the position angle output can be differentiated into velocity and further differentiation produces acceleration for further kinematics analysis. The responses from each joint to different inputs have been shown in the previous graphs. In addition, the exoskeleton movement is animated as simultaneously as the graph of each joint is plotted. However for sinusoidal input, it cannot be used for further analysis as the response does not resemble the actual walking movement.

For a mathematical expression and actual experimental data taken as input and reference to the exoskeleton model with PID controller, the simulated results shows that the modelled exoskeleton design is able to follow given joint trajectories with better control system. From the examples, the exoskeleton model is able to tracks the inputs given to its joints and the exoskeleton design is somewhat viable. Thus the exoskeleton design can be applied for guiding patient wearing it to recover back walking abilities during rehabilitation therapy. Further analysis can be made to improve its output response. The use of MATLAB SimMechanics is useful in the process of modelling and simulation whereby the kinematic responses of the exoskeleton structural design to any inputs can be observed immediately.

CONCLUSIONS

In this study, the process to turn lower limb exoskeleton design into simulated block diagram are presented. The simulation model of the lower limb exoskeleton robot design has been successfully developed and tested with different inputs. The results indicate that by utilizing MATLAB SimMechanics toolbox, the simulation model of the design can be tested and its kinematics responses obtained and can be analyzed before the fabrication of design into prototype. This process can serve as an alternative to kinematic modelling of the lower limb exoskeleton. Further analysis can be performed by designing different controllers utilizing the available Simulink blocks and adding them to the block diagram. By modifying the exoskeleton block diagram model, different control systems can be further developed, simulated and analyzed. Various controllers can be introduced to predict the design efficacy and effectiveness before any hardware and electronics are included into the actual exoskeleton structure.

Hence the walking simulation model of lower limb exoskeleton robot can be used to represent the original design in walking kinematic modelling. The model can be improved by modifying the control system to the joints and giving different type of walking trajectories as reference to the control system. Further work can be done by including a human model wearing the exoskeleton with both the human model and the exoskeleton having different control systems. Through is way the exoskeleton design can be tested to assist the human model in his walking gait. The opportunity in integrating the advantages of CAD design and MATLAB simulation environment as another approach to mathematical modelling and prefabricating the design into actual prototype has been highlighted in this paper.

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