A Wearable Walking Support System Design and Simulation

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Abstract

This research article is focused on the development of a Robotic lower limb exoskeleton model using MATLAB Simulink. The primary aim is to design a dynamic and flexible exoskeleton capable of assisting individuals with lower limb impairments, thus enhancing their mobility and overall quality of life. The model incorporates realistic representations of the lower limb anatomy, encompassing thigh, shank, and foot segments, with carefully integrated joints, constraints, and actuators to emulate natural human motion. A closed-loop control strategy optimizes the exoskeleton's performance, ensuring safe and stable operation during walking and other activities. Extensive simulations are conducted to evaluate the exoskeleton's efficacy, analyzing key parameters such as joint angles, joint torques, and power consumption.

Keywords—component; Lower Limb Exoskeleton; Wearable Walking Support System; PID controller.

1 Introduction

Walking is a fundamental human movement, yet elderly individuals often encounter significant challenges in performing this basic activity due to the deterioration of their lower extremities. Muscle strength loss, often associated with aging, and weaker knee joints are common health problems faced by the elderly, impacting their ability to walk comfortably. Malaysia, with its growing aging population, underscores the urgency of developing walking support systems to meet the increasing demand for assistive devices. However, the country's diverse geography, featuring mountains and uneven terrain, poses additional difficulties for traditional walking support systems such as wheelchairs, canes, and crutches. To address these challenges, engineers, scientists, and doctors have developed various walking support devices, each with its advantages and limitations. Recently, wearable walking support systems have emerged as a promising solution. These robotic devices attach to the user's leg and employ sensors, actuators, and potentiometers to enhance lower extremity strength, protect knee joints, and reduce cardiac system stress during walking or other lower limb movements. This paper presents a novel wearable walking support system model equipped with a PID controller, intended to aid individuals with weakened lower extremities, whether due to aging or injuries. The proposed system delivers torque to the joints through actuators, providing support to the user during movement. Unlike existing linear actuator-based systems, this model offers improved mobility and comfort without the added inconvenience of carrying additional weight or restrictions while sitting. The simulation of the support system aims to showcase its potential as an effective and user-friendly solution.

2 Literature review

Gait analysis is a fundamental aspect of developing a wearable walking support system. It involves a comprehensive examination of the patterns of movement exhibited by the lower extremities during walking. A systematic review conducted by Benson et al. focused on wearable devices for gait analysis, specifically targeting three categories of individuals: healthy younger adults, older adults, and those with various pathologies. The review covered 61 articles, with 47 addressing gait analysis during walking, 13 during running, and one covering both walking and running. Notably, gait analysis revealed distinct differences in variability, regularity, and symmetry between older adults and healthy young adults during the gait cycle. Instrumented measurements of joint kinematics and kinetics lie at the core of gait analysis.

The information derived from gait analysis serves as a basis for developing the algorithm and structure of the support system. Gait analysis can be categorized based on its intended purpose. It is predominantly employed for clinical rehabilitation, helping individuals with lower extremity injuries or posture-related issues. Moreover, gait analysis finds extensive use in clinical research, where it serves to study specific conditions affecting groups of individuals or assess the impact of interventions. While the criteria for clinical testing and clinical research differ, both are essential in advancing our understanding of gait patterns and the development of effective walking support systems.

For the development of a wearable walking support system, gait analysis offers critical insights. It aids in understanding the user's unique walking pattern, including foot angles, joint range of motion, and center of gravity placement. This valuable information allows for the customization of support systems to meet individual needs. Furthermore, gait analysis helps identify areas of weakness or instability in the user's gait, providing a targeted approach for support. Additionally, by analyzing the user's gait improvements can be made to enhance system efficiency. Gait analysis is an indispensable tool in developing wearable walking support systems. Its role in understanding walking patterns, identifying areas of weakness, and measuring the effectiveness of support systems makes it invaluable in creating personalized, efficient, and effective solutions for individuals with lower extremity challenges. The systematic and comprehensive examination of gait patterns helps in advancing the field of assistive technologies and rehabilitation, ultimately improving the quality of life for those in need.

2.1 Motion monitoring system

Human motion tracking systems are the systems used to conduct gait analysis, due to their preciseness and capabilities. Human motion tracking systems can produce real-time data using modern sensor technologies. Human motion tracking systems are usually used either as a substitute rehabilitation environment that could be installed in the homes of patients or used to conduct gait analysis.

In the UK, 135,000 people experienced stroke in the year 2001and 2002, and required admission to hospital [1]. Therefore, the demand for technologies like the Human motion tracking systems increased heavily. Generally, the study classifies the human motion tracking system into four categories: Visual based systems, non-visual based systems, a combination of both, and Robot-aided tracking. The inertial accelerometer sensor would be suitable for a portable device due to its physical compatibility and lightweight. To collect human movement patterns and detailed information, sensors are used in non-visual based systems. Mostly they are mechanical based. Exoskeletons have a left-right pair, it is effective to wear based on one's comfort.

In general, it is important to have a lightweight material and an actuator, for the driving section of the robotic exoskeleton fixed on the knee part [2].

To support antigravity muscles on the lower extremities a model-based control algorithm without using biological signals, can be fixed to the knee joint for better support. Based on a human model one can calculate all the interaction forces acting on the left thigh moment [3].

2.2 Wearable walking support systems

Exoskeleton robots, also known as wearable walking support systems, have been the subject of development and research for several decades. One of the earliest exoskeletons, the Hardiman, was developed by General Electric in 1965, primarily for strength augmentation of the arms and legs [4]. Over the years, exoskeleton technology has advanced significantly, leading to the creation of various exoskeletons with diverse applications. One notable example is BLEEX, developed by Zoss, Kazerooni, and Chu at the University College of Berkeley in 2005, BLEEX is a lower limb exoskeleton that operates as the first energetically autonomous robot of its kind. Designed to be worn by users, BLEEX enables individuals to carry heavy payloads while maintaining walking endurance, making it valuable for load-carrying applications. Subsequently, Kazerooni, in collaboration with Ekso Bionics, created the HULC exoskeleton in 2009, which utilizes hydraulic power to allow soldiers to walk longer distances while carrying heavy loads [5]. Kazerooni's contributions have earned him the moniker "Father of modern exoskeleton." Exoskeletons have also proven to be beneficial beyond augmentation, with applications in support and assistance. For instance, Ikeuchi et al. from Honda developed a bodyweight support exoskeleton in 2009, reducing the user's perceived weight during walking by redistributing weight to the support structure [6]. In a later advancement, Honda created the Honda Stride Management Assist in 2014, which boosts user hip motion during walking and has demonstrated efficacy in assisting patients with Parkinson's disease by increasing step length [7]. Rehabilitation exoskeletons form another category, aiding patients undergoing therapy under specialized supervision. Notable examples include

BLEEX, developed by Kazerooni, Zoss, and Chu, and Kawamoto et al.'s HAL-3 (Hybrid Assistive Leg) [8]. To support the hip joint by providing flexion and extension torques, and to walk for extended periods carrying heavy loads, these devices are used. To understand well the exoskeletons, researchers used human gait analysis, which involves understanding various human walking movements and their mechanics behind and their involvement in to various joints [9], [10]. Such studies are pivotal in designing effective exoskeletons. For example, Miao et al. explored four human movements involving the lower limbs studying walking, running, jumping, and squatting, to determine suitable action states for exoskeleton therapy [11]. However, developing prototypes of exoskeletons can be prohibitively expensive due to the cost of fabrication and the uncertainty surrounding the prototype's efficacy.

To address this challenge, simulation using computer-aided design (CAD) software has emerged as a cost-effective alternative. Software like Solidworks, AutoCAD, and Fusion360 allows designers to create and simulate exoskeleton structures before actual fabrication, ensuring efficiency and effectiveness. Researchers have utilized SimMechanics in MATLAB Simulink [12], SolidWorks [13], and ADAMS in MATLAB for simulation purposes. The primary goal is to develop a simulation of a wearable walking support device (exoskeleton) design using Fusion360 software. The two- legged exoskeleton design aims to provide knee joint support using BLDC motors without relying on biological signals. By simulating the design in Fusion360, stress analysis, support efficacy, and other critical results will be obtained, reducing the need for costly physical prototypes. This approach contributes to the advancement of exoskeleton technology and facilitates the development of efficient and affordable walking support systems.

3 METHODOLOGY

3.1 PROCESS

In the upcoming chapter the main procedures to develop the wearable walking support system will be covered with explanation and illustrations. The chapter will include all the materials used, as well as the explanation of the wearable walking support device.

3.2 METHODS and MATERIALS

The system design is modelled as a CAD design. A control system was designed for the lower limb exoskeleton model, Specifically, a PID controller. The Model is then further simulated using MATLAB's add-on Simscape Multibody (formally SimMechanics), that provides a multibody simulation environment for 3D mechanical systems, such as Robotic systems. The PID controller was designed using the Newton-Euler equations to calculate the inverse dynamics of the Lower part.

3.3 WEARABLE WALKING SUPPORT SYSTEM

The process of designing the Wearable walking support system started with designing a 3D CAD design using Fusion360. The components of the exoskeleton included feet, thigh rods, knee rods, back, and holders for the control components. The model of the exoskeleton designed is illustrated in Fig. 1. The model is a two-legged exoskeleton, which is connected at waist. The model has 6 Degrees of Freedom (DOF) and joints with each leg containing three: hip, knee, and ankle joints. The CAD design does not include the actuator nor gear; however, the simulation model includes an actuator block.

Fig.1 CAD design of the lower part.

Following the Design of the Lower Limb Exoskeleton in Fusion 360, the file is imported into Autodesk Inventor. Autodesk was chosen due to a unique feature that is not present in many computer-aided design (CAD) applications/software, which is to allow the installation and implementation of the Simscape Multibody add-on. This feature provided a less complicated procedure to help convert the files from their original (step or stl) format to an (XML) format included with their design specifications, which can be imported into MATLAB's Simscape Multibody add-on to allow for simulation.

3.4 DESIGN AND SIMULATION PROCESS FLOW

The process of developing the Lower Limb Exoskeleton is explained in a block diagram as shown in Fig. 2. The process begins with designing a 3D CAD Model for the exoskeleton using suitable CAD software. Preferably, either Autodesk Inventor, SolidWorks, or Creo, as the mentioned software is the only software that supports the Simscape Multibody add- on. The next step is to import the design into MATLAB using the import function "smimport ('xml file name');". Once the xml file of the exoskeleton model is imported, a block model of the exoskeleton is created in Simulink. The block model is then rearranged with the addition of the actuators, the joints, and the control systems for each joint. There are 6 DOF/joints in the lower limb exoskeleton, 3 DOF/joints in each leg with one degree of freedom in each joint of the three joints hips, knee, and ankle. The joints revolve as the joints should move only in the sagittal plane. Once the block diagram as Fig. 3 is rearranged, the simulation is run, and the results can be obtained. There are 6 DOF/joints in the lower limb exoskeleton, 3 DOF/joints in each leg with one degree of freedom in each joint of the three joints hips, knee, and ankle. The joints revolve as the joints should move only in the sagittal plane.

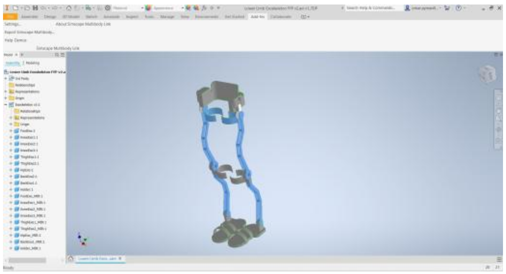


Fig.2 The CAD design of the Lower Limb Exoskeleton in Autodesk Inventor.

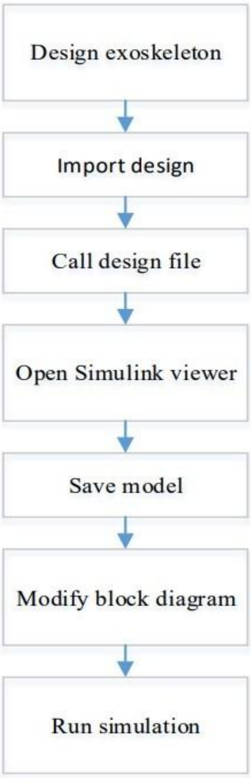


Fig. 3 Process flow of the Design and Simulation.

4 PID Controller

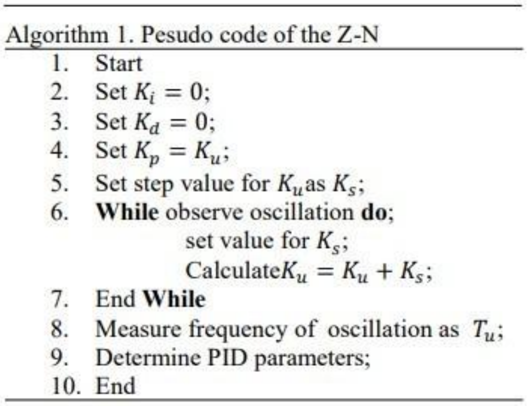
A PID controller has been selected to control the trajectory of the joints. PID controllers are very common due to their simplicity, also they consist of three basic control actions (proportional, integral, and derivative), each of which contributes to the overall control effort, other than simplicity, PID controllers provide stability. The error of the system is the difference between the desired and actual angular trajectory of each joint.

$$\theta_e = \theta_{Actual} - \theta_{Desired} \tag{1}$$

The difference between the actual and desired of the PID are the error θ_e. The equation of PID controller is as follows:

$$\tau = K_p\theta_e + K_i\int_0^{\tau}\theta_e dt + K_d\frac{d\theta_e}{dt} \tag{2}$$

The K_p, K_i, and K_d are the gains of the PID. The value of the gains determines the position of the joint; each joint requires a different gains value. The gains value can be obtained from the Ziegler-Nichols (Z-N) method for tuning the PID controllers. The method determines the PID parameters through identifying the critical gain and critical period of the system. The Pesudo code of the Z-N is explained in algorithm 1.



Algorithm 1. Pesudo code of the Z-N

```
1.  Start
2.  Set $K_i = 0$;
3.  Set $K_d = 0$;
4.  Set $K_p = K_u$;
5.  Set step value for $K_u$ as $K_s$;
6.  While observe oscillation do;
        set value for $K_s$;
        Calculate $K_u = K_u + K_s$;
7.  End While
8.  Measure frequency of oscillation as $T_u$;
9.  Determine PID parameters;
10. End
```

PID parameters are determined as follows,

$K_p = 0.7\times K_u$ (3)

$K_i = 1.75 \times (K_u/T_u)$ (4)

$K_d = (21 \times K_u\times T_u)/200$ (5)

where K_u is the value of K_p when the value of both K_i and K_d is equal to zero, while T_u is the frequency of the of the oscillation. Table 1 shows the gain values of each PID and the PID parameters values for each joint.

Table 1 The gain values of each PID and the PID parameters values for each joint.

Joints	Kp	Ki	Kd
Hip	46	142.213	4.28
Knee	35	103.578	3.35
Ankle	5.14	15.532	0.5125

5 RESULT and DISCUSSION

5.1 JOINT TRAJECTORY

Fig. 4, Fig. 5, and Fig. 6 show the desired and actual joint trajectories. Because the movement is symmetrical, only the findings for the joints of the left leg are shown. We can see that the joint positions are similar to the desired ones, although they are not identical. The collision of the foot exoskeleton with the ground is one explanation for such a disparity. This effect may be mitigated by increasing the derivative gain. A higher derivative gain, on the other hand, produces in excessive torque, making the bracing's trajectory unstable. Despite minor variations in the required location, the bracing stays stable.

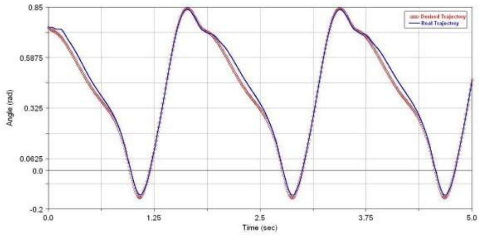


Fig.4 Angle(rad) x time(sec) for joint 1, left hip joint.

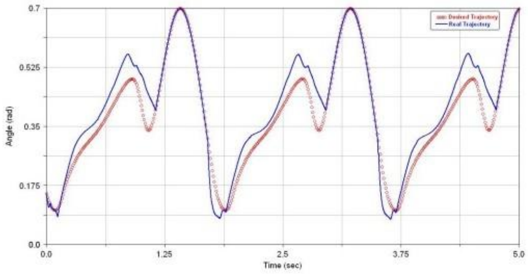


Fig.5 Angle(rad) x time(sec) for joint 3, left knee joint.

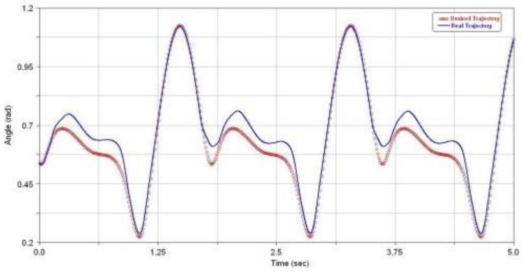


Fig.6 Angle(rad) x time(sec) for joint 5, left ankle joint.

5.2 INTERACTION FORCES

The interaction forces can be calculated, the behavior of forces is shown in Fig 7, Fig 8. The impact with the ground results in fast changes. According to the graphs, the majority of these variances occur during the same period.

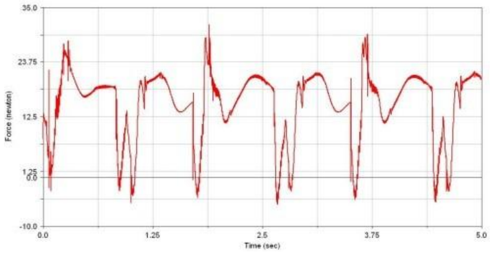


Fig.7 Interaction Torques acting at the torso.

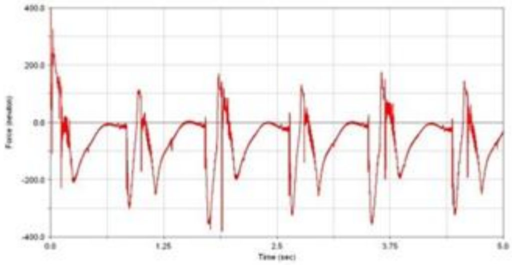


Fig.8 The interaction forces acting on the left thigh.

5.3 DISCUSSION

The results obtained show that the structure of the exoskeleton modelled using Simscape Multibody as a Simulink block diagram can be actuated at each joint. The process is done by adding an actuator block to actuate the joints, a sensor block, that is added as feedback from the output to form a control system. In addition to this, further kinematic analysis could be conducted by differentiating the position angle output into velocity which is then further differentiated to come out with the acceleration. The joint trajectories were simulated, in addition to the applied torques inside the joints being illustrated. The exoskeleton has shown reliability in the majority of the results. The results obtained show that the proposed exoskeleton model has the capabilities to support the walking movement of a human. Therefore, based on the results, the proposed wearable walking support system should be of assistance to individuals with weakened lower extremities, or individuals with lower limb impairments whether it is due to age or injuries. More research can be done to improve its output response.

6 CONCLUSION

In conclusion, this paper successfully developed and simulated a lower limb exoskeleton with PID control using MATLAB Simulink. The implementation of PID control allowed precise and responsive joint angle regulation, ensuring smooth and natural gait patterns. The simulation results demonstrated the exoskeleton's efficacy in tracking desired trajectories, responding to external disturbances, and minimizing tracking errors. The use of MATLAB Simulink provided a robust platform for modeling and tuning the PID controllers, enabling iterative improvements before physical prototyping and testing. The successful simulation of the exoskeleton signifies a significant advancement in wearable walking support systems, offering great potential for assisting individuals with mobility impairments. As future work, advanced control algorithms and real-world testing will further enhance the exoskeleton's performance and usability, revolutionizing the field of assistive technologies and rehabilitation.

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