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The Concept of Flexible Lower Limb Powered-Exoskeleton for Human Performance Augmentation: A Review

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Abstract

This review covers the lower limb powered exoskeleton by using the two-links flexible to generate the dynamic model for flexible robotic legs. The exoskeletons are defined as wearable robotic mechanisms for carrying loads. Therefore, this paper covers various aspects of two-flexible links in term of modeling methods, dynamical analyses, and control schemes. An introduction to Proportional, Integral, Derivative (PID) controller at the short literature review is provided to improve the performance of flexible robotic legs. This review summarizes the overview of augmenting exoskeletons, types of lower limb exoskeletons, biomechanics of human gait, the mathematical models of two-flexible link, and the control approach of the two-link flexible to generate flexible lower limb powered exoskeleton for carrying load based on the concept of two-link flexible.

1. Introduction

Musculoskeletal disorders (MSDs) is one of the most common occupational health problems and costly health problems among working populations, and constitute a major cause of disability [1]. MSDs include lower limb disorders that affect hip, knee and leg. Lower limb disorders and injuries, especially leg problems are real issues in many workplaces. Industrial workers are frequently exposed to injury at work due to carrying heavy loads, and according to the Social Security Organization of Malaysia, the severity of the injuries that can contribute to poor occupational health. In the SOCSO annual reports, it was stated that annually 4750 industrial workers suffered from injuries in leg [2].

During the past decade, exoskeleton robotics (wearable robots) have been developed according to the supported parts of the human body. Exoskeletons are defined as wearable robots that integrate human physique with robotic machines by combining human intelligence with the power of the robots into a single mechanism [2]. Exoskeleton systems are robotic manipulator which are wearable and move with the user synchronously. Recently, exoskeleton systems are used for human integration applications such as rehabilitation, military, industrial for heavy-weight lifting, and civil defense [3]. The exoskeleton assistive devices have been developed in the last six decades for various manageable advantages, such as allowing user to traverse irregular terrain surfaces compared to wheeled vehicles [4].

Lower limb powered-exoskeleton is wearable system which could benefit human wearers perform a number of different tasks include, workers and soldiers in order to carry heavy loads, or walk long distances under an emergency situation [5], decrease the burden in physically demanding tasks and apply rehabilitation treatment to patients who have suffered major trauma, for instance, stokes [6]. Robotic exoskeletons are divided into two wide categories based on their usage. First category encompasses assistive devices (medical exoskeletons) for people with muscle weakness spinal cord injury; while the second category (non-medical) applies to individual performance and efficiency augmentation exoskeletons for increasing endurance, strength and physical abilities by able bodied people [7].

Biomedical exoskeletons provide a wide variety of applications that includes the physiotherapy techniques and rehabilitative exercises [8]. Besides, medical exoskeletons have been developed for paraplegics, rehabilitation, amputees and compensation [9]. Medical lower limb exoskeletons are employed to assist people who have lower limb paralysis or weakness in walking, lower limb exoskeletons can be utilized with matters with complete or incomplete SCI or other type of neurological diseases such as stroke, multiple sclerosis [10]. More recently, a walking assist exoskeleton called the Hybrid Assistive Limb (HAL) has been developed by B. Chen et al (2016) for many applications such as supporting healthy people to enhance their strength and enable them to walk as normal people [11].

According to records from the past 12 years the non-medical exoskeletons were developed for soldiers, workers, healthy elderly and general purpose [6]. Military exoskeletons allow soldiers to carry the load of weaponry, equipment, and transport medical support, enable soldiers to carry heavy equipment over long distances without getting tired [12]. Industry needs lots of manual operations that always limit the performance of the workers due to physical exhaustion. Exoskeletons could be used to increase the abilities of moving, handling, and allow the workers to carry the loads safely [13]. One of the most advance exoskeletons for carrying load is the Berkeley Lower Extremity Exoskeleton (BLEEX) which has been developed at the Human Engineering Laboratory of University of California, Berkeley. BLEEX is an energetically autonomous exoskeleton capable of carrying its own weight plus an external payload. BLEEX comprises two anthropomorphic legs driven by hydraulic actuators to power the hip, knee, and ankle [14]. This paper summarizes the overview of augmenting exoskeletons, types of lower limb exoskeletons, biomechanics of human gait, the mathematical models of two-flexible link, and the control approach of the two-link flexible to generate flexible lower limb powered exoskeleton for carrying load based on the concept of two-link flexible.

2. Overview Of Augmenting Exoskeletons

Augmenting exoskeletons have been developed with a view to enhance the strength of the wearer and apply assistive torques to the wearer's joints and support any payload being carried by the wearer [11]. Augmenting exoskeletons help otherwise healthy people to perform physical tasks that are normal individual capabilities such as being able to lift or carry many times one's own weight while walking or working faster for sustained times with minimal physical exhaustion [13]. There are various designs of lower limb exoskeletons that offer different purposes for the wearer, such as load transfer to reduce the metabolic cost of the wearer for carrying loads and ultimately enhance the strength of the wearer [15].

Examples of the augmenting exoskeletons called as non-medical exoskeletons that have been developed such as BLEEX, HAL-5, MIT, HULC and SARCOS Exoskeleton. The Berkeley lower exoskeleton has been developed at the Human Engineering Laboratory of UC, Berkeley. The BLEEX is an exoskeleton for heavy load carrying having its own no-board battery and attached to the human foot and back. Each leg has seven Degrees of Freedom (DOFs) as shown in Figure 1 (a) with three degrees of freedom at the hip, one at knee and three at the ankle. The hip, knee, and joints are powered in the sagittal plane with linear hydraulic actuators [16]. The dynamic model of the BLEEX has been developed by using the simplified model of the robot leg as the three-segment manipulator [17].

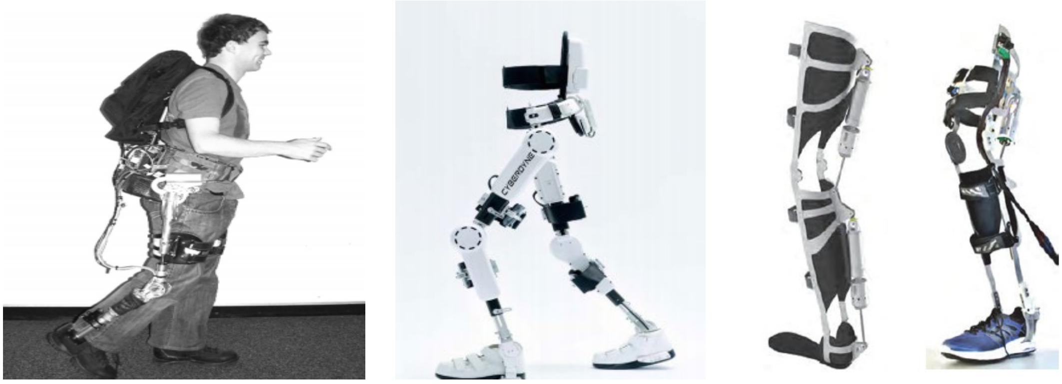
(a) **(b)**

Fig. 1 *(a) The Berkeley Lower Extremity Exoskeleton [17]; and (b) Sarcos Exoskeleton [18]*

BLEEX consumes an average of 1143 W of hydraulic power during level-ground walking as well as 200 W of electrical power for the electronics and control. In contrast, a similarly size 75 kg human consumes around 165 W of metabolic power during level-ground walking [19. Two different control schemes are proposed for the DLEEX. The first control scheme is sensitivity amplification controller to measure human contribution or interaction forces and seeks to minimize the use of sensory information from the human, the second hybrid assistive control scheme that switches based on gait phase between sensitivity amplification the position control regulating desired torque and generate locomotion when the contact location between the pilot and the exoskeleton [17]. The performance of the BEELX, the user can carry a load of up to 34 kg while walking at the average speed of 0.9m/s and can walk at speeds of up to 1.3m/s without carrying the load [17].

Sarcos Research Corporation (Salt Lake City, UT) has developed a full body called Sarcos Exoskeleton as shown in Figure 1(b) that increases strength and endurance of the suit's operator, carrying its own power like BEELX. Sarcos Exoskeleton is designed to mimic the movements of the human joints by using advance hydraulically actuated exoskeleton instead of linear hydraulic actuators [18]. It has rotary hydraulic actuator and the force sensor are used to control the motion. The user cannot bend his feet as the metal plate is containing the force sensing elements [19]. The Sarcos Exoskeleton could carry a load around 84 kg and has been successful in demonstrating the number of impressive feats, wearer can carry 68 kg during walking at 1.6 m/s and the wearer standing on one leg while carrying another person on their back [20].

Meanwhile, the MIT Exoskeleton was developed by Massachusetts Institute of Technology as shown in Figure 2(a), it is designed based on quasi-passive that does not use any actuator for introducing or adding power at the joints but is based on the release of energy stored in springs [21]. The 3 DOF hip utilizes the spring-loaded joint during extension/flexion and then released during flexion. This spring mechanism is design to allow the user to freely swing the hip in the flexion direction [19]. The control is motivated by human walking data, uses the same concepts of human walking for carry a load and supporting the movement of the body. The MIT exoskeleton revealed an important reduction in metabolic cost of walking versus the same exoskeleton without the spring at hip, ankle and the damper at the knee, thus shows the utility of the MIT element. MIT exoskeleton weighs 11.7 kg without a payload and requires 2 W of electrical power during walking and supported a 36 kg load while walking at speed 1 m/s [18].



(a) **(b)** **(c)**

Fig. 2 *(a) MIT Exoskeleton [21]; (b) The Hybrid Assistive Limb HAL-5 [22]; and (c) the KIT Exoskeleton [23]*

The Hybrid Assistive Limb (HAL), also known as HAL-5, is an exoskeleton that has been developed by the University of Tsukuba, Japan for many applications for both performance augmentation and rehabilitative purposes as shown in Figure 2(b) [11]. HAL has both unilateral and bilateral designs that actuate the knee and hip joints movement by sensing very weak bioelectric signals on the surface of the human skin [24]. The leg structure of the hybrid assistive limb (HAL-5) exoskeleton powers the flexion joints at the hip and knee by DC motor with harmonic drive placed on the joints. The HAL is passive on the ankle and the lower limb interface with user a number of connections special shoe with ground reaction force sensors [25]. HAL-5 system does not transfer the load to ground surface, but augments joint torques at the hip, knee, and ankle. These sensing modalities are used in two control systems that together determine user intent and operate the suit: an EMG-based system and a walking-pattern-based system. Reported drawbacks of the system are; it takes two months to optimally calibrate the exoskeleton for a specific user. The total weight of the full-body device is 21 kg and the effectiveness of the lower limb components of the exoskeleton [15]. However, wearer of HAL can carry up to 40 kg on the arms. The HAL-5 allows the workers to carry heavier loads up to 70 kg [26].

The KIT exoskeleton is new lower limb exoskeleton with series elastic actuators was developed by Karlsrushe Institute of Technology, Karlsruhe, Germany is used for augmentation of human performance and also for rehabilitation purposes as shown in the Figure 2(c). The KIT has two active DOFs in the ankle and the knee, also it consists of three DOFs in which the knee joint is actuated by linear series elastic actuators using the force based interface between the human and the exoskeleton using control scheme for knee joint [23].

The Body Extender (BE) is a full body exoskeleton for transporting and handling a heavy load. It comprises two identical legs with 6 DOFs each and two identical arms with 5 DOFs each. All 22 DOFs are actuated by highly actuation units. The approximate weight of the full body exoskeleton with power supply is 160 kg and can transport loads up 10kg to100 kg at a walking speed of 0.5 m/s [27].The Asian Institute of Technology Leg Exoskeleton-I, or ALEX-I, in Pathum Thani, Thailand has been developed to help a patient who suffered from the lower limb injury or immobility with loss of power on the lower limb to walk as normal people and this exoskeleton consists of 12 DOFs (6 DOFs on each leg, 1 DOF in the knee, 3 DOFs in the hip and 2 DOFs in the ankle) and controlled by 12 DC motors. The weight of this exoskeleton with backpack is about 117.5 kg and it can carry the both external loads and the user [28].

Table 1 *Comparison between the performances of the existing augmenting exoskeleton*

Previous research	Power source	Actuator type	Control scheme	Advantages	Disadvantages
BLEEX [17]	Internal combustion	Linear hydraulic	Sensitivity amplification	Carry a load of up to 34kg while walking at the average speed of 0.9m/s.	Does not follow pilot's motion exactly. Heavy and noise. Large torque requirements.
Sarcos XOS 2 [18]	External tether	Linear and rotary hydraulic	Sensitivity amplification	Wearer can carry 68kg during walking at 1.6m/s.	Requires power supply. Heavy. Metabolic data unavailable Not designed for normal population
MIT Exoskeleton [21]	Non	Non	Controlled energy release	Supported a 36kg load while walking at speed1m/s. Light weight. Does not use any actuators.	Limited mobility. Increase metabolic cost.
HAL-5 [22]	Unspecified battery	DC Motor	Model-based control with intent estimation	Carrying loads up to 70kg. performance for augmenting and rehabilitative purposes	Expensive. Needs extensive calibration before use. Metabolic data unavailable. Heavy weight system with complex sensing modalities
KIT Exoskeleton [23]	Non	Linear series elastic actuators	PID Controller	Support a body weight of 100kg and 120Nm joint torque while person walking at a speed of 1m/s.	Need a long calibration process and the sensor noise in changing the conditions.

The body extender (BE) [27]	Grounded battery pack 17.5 kWh at 0.9 kW	DC Motors	Force Controller	It can transport loads up 10-100kg at a walking speed of 0.5m/s	Requires several repeated trial. Slow speed. Difficulties in bimanual manipulation

3. Biomechanics Of Human Gait

The gait is the manner of human walking motion and walking described as the method of locomotion which involve the use of the two legs and alternately in order to provide both support and propulsion movement. In gait process has to basic elements which are a periodic movement of the feet from one position of support to the next position and sufficient ground reaction forces to support the body through the feet [29]. Walking is three dimensional as shown in Figure 3, the reference planes of the human body in the standard anatomical position [30]. Sagittal plane is any plane which divides a human body part into right and left portions, a transverse plane divides the human body portion into upper and lower parts and the frontal plane divides a body into front and back portion. In this study only focuses on the sagittal plane as the largest motions, torques and powers are in this plane. The movement of the human and motion are very complex due to the number of degrees freedom of the human body [32]. The movement of the human body during daily life that involve large power and torque that are performed mostly in the sagittal plane [33]. The walking, running and standing are included in these motions. In the previous researches focused on the actuation of joint in sagittal plane especially in flexion/extension of hip, ankle and knee [4].

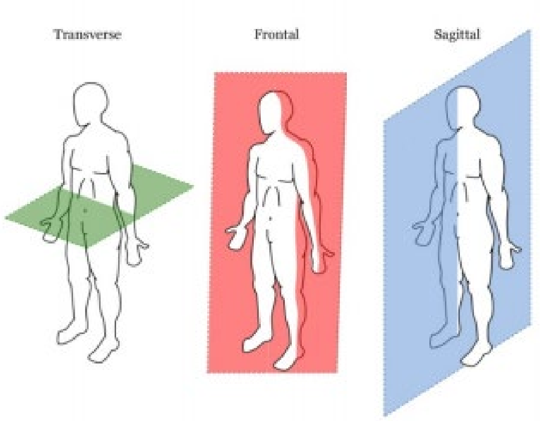


Fig. 3 *The reference planes of the body in the standard anatomical position [31]*

3.1 Gait Cycle and Gait Phases

The gait cycle is a repetitive movement pattern of walking [34]. Meanwhile, the human body moves forward, one limb initiate contact with the supporting of the ground act as source of support and other limb moves to a new support site. Then a limb opposite their roles, that number of events is recurred by each limb with movement until reached the destination. A single series of those function by one limb is known as the gait cycle [29]. Each gait cycle can be divided into two phases, the stance phase (weight-bearing) and swing phase (non-weight-bearing). The stance is used to designate the entire period when the foot is on a ground, stance starts with initial contact and the swing pertains to the time when the foot is in the air for the limb, swing begins when the foot is raised from the floor [35]. The single cycle is the motion between the heel strikes of one foot to the heel strike of the same foot on the following step. Therefore, during one cycle the foot can be off the ground (swing phase) or on the ground (known as stance phase). The stance phase represents approximately 60% of the cycle during one gait cycle in walking, while the swing phase occurs the remaining 40% [36]. There are seven events which subdivide the gait cycle into seven periods, four of the seven events occur in the stance and three of the seven events occur in the swing phase, the seven events during the gait cycle are (1) initial contact, (2) opposite toe off, (3) heel rise, (4) opposite initial contact, (5) toe off, (6) feet adjacent and (7) tibia vertical as shown in Figure 4 [29].

The stance phase also known as contact phase divided into loading response, mid-stance, terminal stance and pre-swing while both feet are on the ground or from the moment while the toe of the limb initial contact with the ground up to the movement of the toe of the limb during detaching the ground. The swing phase divided into initial swing, mid-swing and terminal swing when one foot is on the ground or when the toe is off from supporting ground up to the moment of next initial contact with ground [37] [38].Analysis the human gait cycle by phases to recognize functional significance of the different motions that generated in the individual segments and joints [39], a walking gait cycle of the normal individual is divided into eight gait phases as shown in Figure 5. The consecutive combination of the phase also allows the limb to perform three fundamental tasks, which are the weight acceptance, single limb support and limb advancement. Weight acceptance starts the stance phase and employs the initial two gait phases (initial contact and loading response). Single limb support remains stance phase with the following two phases of gait (mid stance and terminal stance). Limb advancement starts in the last phase of stance (pre-swing) and then remains the three phases of swing (initial swing, mid swing and terminal swing) [40].

The weight acceptance is the most challenging task in the gait cycle because their functional patterns are required which are the preservation of progression, shock absorption and initial limb stability, the challenge is the immediate transfer of body weight onto the limb that has completed swinging forward and has unstable alignment, two gait phases are involved in this task, phase 1- initial contact which is comprises the moment once the foot touches the floor. The joint postures presented at this time determine the limb's loading response pattern. Phase 2- loading response which is the initial double stance period and starts with initial ground contact and remains. When the other foot is lifted foe swing, the knee is flexed for the shock absorption by using the heel as the rocker [41] [42].

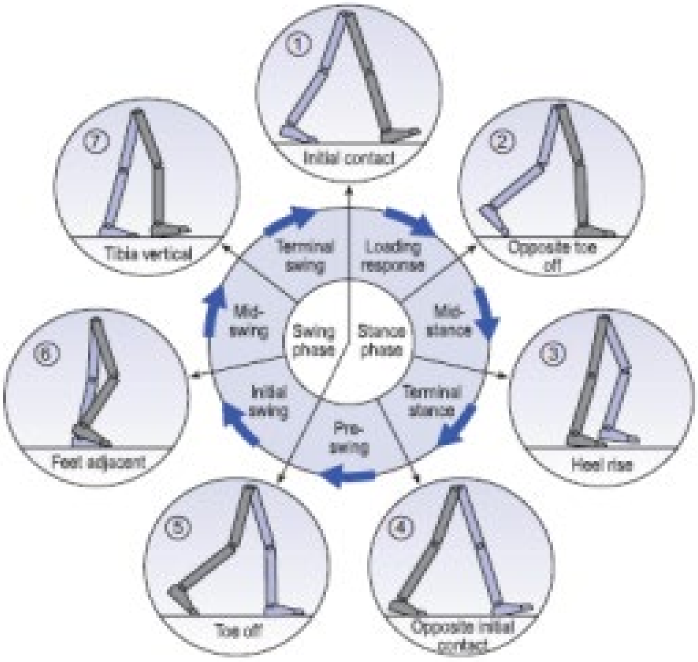


Fig. 4 *Events in the Gait Cycle [37]*

Single limb support is the lifting the foot for swing begins the single limb support interval for the stance limb and this continues until the opposite foot again contacts the floor. Throughout the resulting interval, the one limb provides the total responsibility to get supporting body weight in the both coronal and sagittal planes when progression needs to be continued [31]. Single limb support is involved two phases which are phase 3- mid stance that is in the first half of single limb support, the limb advances over the stationary foot by ankle dorsiflexion ankle rocker while the knee and hip extend, the opposite limb is advancing in its mid swing phase. Another phase in single limb support is phase 4- terminal stance which is occur in the second half of single limb support, the stance begins with the heel rises until the other foot strikes the floor, in this phase, the body weight moves ahead of the forefoot [43]. Limb advancement to meet high demands of advancing the limb preparatory posturing begins in stance, then the limb swings through three postures as it lifts itself, advance and prepares for the next stance interval. There are four gait phases in the limb advancement which are pre-swing, initial swing, mid swing and terminal swing. The pre-swing is the final phase of stance begins with initial contact of the opposite limb and finishes with the toe-off and this phase known as weight transfer [29]. The initial swing phase begins with the lifting of the foot off the ground when the swing foot is opposite the stance foot. The mid swing is the second phase of the swing phases that begins when the swinging limb is opposite the stance limb and ends when the swinging limb is forward and the tibia is vertical. Advancement of the limb anterior to the body weight line and other limb is late mid stance.

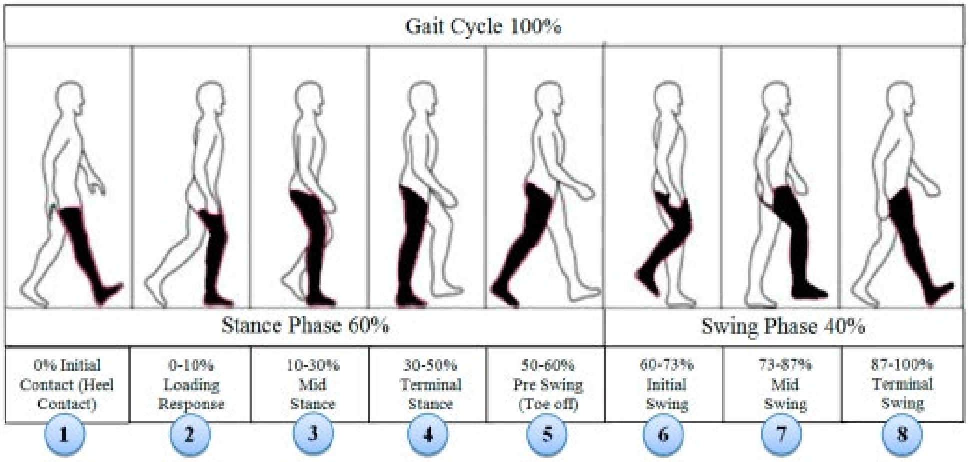


Fig. 5 *The eight main phases in Gait Cycle [44]*

4. Dynamic Modelling of Link-Based Robot

The dynamic modeling of a robotic leg is an important topic in order to design and control the robotic leg and the dynamic model of a robotic leg involves the effects of gravity, inertia and Coriolis onto robotic system. Dynamic model of flexible robotic leg could be derived by using the mathematical model [45].

4.1 Athematical Model

The mathematical model of a link-based robot differs according to the number of degrees of freedom (DOFs) out of different consideration and purpose. In this section will describe the modelling techniques of two link flexible and multi-link flexible. Vakil et al. [46] derived the dynamic model for planar flexible link and joint manipulator based on the concept of two-link manipulator by combining the assumed mode shape and the Euler Lagrange's equation with taking the consideration of the mass moment of inertia and tip mass. Ahmad et. al. developed dynamic model of two-link flexible manipulator system with payload based on the equation of motion and the kinematic mode based on the standard frame transformation matrices for model displacement and the rigid rotation [47]. The model was developed by using Lagrangian approach and the links were modeled as the Euler-Bernoulli beams. The dynamical modeling and characterization of a two-link flexible robot manipulator incorporating structural damping, hub inertia and payload using combine Euler-Lagrange and Assumed Mode Method (AMM) as shown in Figure 6. The model has been validated by using numerical simulation [48].

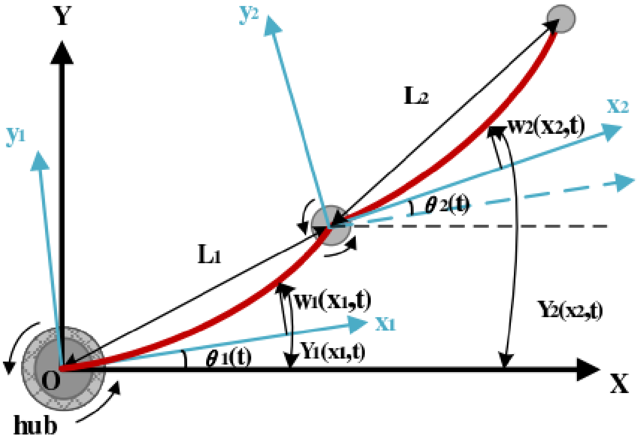


Fig. 6 *Structure of a two-link flexible manipulator [49]*

The dynamics equations of motion of two-link manipulators derived by using the Lagrangian approach and the actuators dynamics are included in the modeling, and the links are modelled as Euler-Bernoulli beams. The AMM to reduce the equation of motion into the ordinary differential equation [50]. The Mathematical modeling for two flexible link manipulators derived by utilizing the finite element method and Lagrangian approach. Initially, the authors derived a mathematical model for a single link and the extended the modeling for multi-links [51].

In another research has established coupled dynamic model by using Lagrange equation and assumed modes to describe two-link piezoelectric flexible manipulators and calculating generalized force, potential energy and kinetic energy. The authors used the modal function for second link in order to obtain the stress of its surface layer by optimal placement of actuator or sensor on the second link [52].

R. M. Mahamood (2014)[53] modeled two flexible link robot manipulators as Euler-Bernoulli beams by using assumed mode method and Lagrange for reduce the Partial Differential Equation of motion (PDE) into Ordinary Differential Equation (ODE) and the authors highlighted that the most method to describe the system dynamics is the Lagrange approach and assumed mode method. The authors have studied the two-link flexible joint manipulators by using Lagrange dynamics equation and derived the kinetic equation of the arm model [54]. In another research has analyzed the reliability of the dynamic strength and dynamic stiffness of the two link flexible robot manipulators using Monte Carlo method and the links of the manipulator are considered as the homogeneous Euler beam and the Lagrange's equation used to derived the dynamic equations [55].

Luo Jian et al. [56] expressed the model that considered as Euler Bernoulli beam and the deflection of the n-link flexible manipulator using finite element method. Lagrangian equation used to obtain the dynamic equation for n-link flexible manipulator. The model reduction into couple system using singular perturbation theory for time scaled, to fast varying subsystem. The authors emphasized that the model expansion and the finite element method are the best methods for the modeling flexible manipulators. Madani et al derived the equation of motion for the three linkage and three linkages rigid links are connected to the flexible link by employed the Lagrange equation [57].

4.2 Forward and Inverse Kinematics

In order to establish the coordinate systems of the flexible robotic leg that includes n-link, the forward kinematic method can be employed for deriving the mathematical model of the flexible robotic leg. Denavit-Hartenberg parameter used to obtain the transformation matrices for the linkages and joint and the DHPs consist of link length, link offset, link twist and joint angle [58]. In another research, generated the locomotion patterns of a robotic model using Denavit-Hartenberg parameter notation and derived the dynamic model of the robotic leg using Lagrangian equation, [59]. Sebastian et al. defined and analyzed the 3-link kinematic model of human leg based on the optimizing the manipulability, and defined quantitative measures of manipulability using forward kinematics [60]. Inverse kinematics is important in defining a trajectory for the flexible robotic leg in term of joint space based on the desired locations of leg in the global Cartesian space. Inverse kinematics is determined and solved by using transformation matrix and then solve for each of the angle [58].

4.3 Two-Link Rigid

E. H. Hasnaa and B. Mohammed [61] have derived the dynamic model of the two link rigid manipulator using Newton Euler approach, the nominal model and the nonlinearity of the system were determined using the identification method to achieve robust stability and a good performance against dynamic disturbances, uncertainties and actuator noises, two robust controllers were developed which are H_∞ mixed sensitivity and μ synthesis controller. In [62] has been presented the Lagrange-Euler method for deriving the dynamics of two link rigid manipulator, two different robust control strategies H_∞ and μ synthesis were used and compared, based on the results that show μ synthesis controller has superior robust performance of the proposed two robust control method.

D. Popescu et al [63] studied the neural and adaptive control of a rigid link manipulator and modeled the robotic manipulator as a set of number rigid bodies connected in series with one end fixed to the ground and other end free with two revolute joints, based on the simulation that showed the neural controller obtained better results compare to adaptive control strategies. In another research proposed an adaptive tracking control method that can be deal with the kinematics uncertainty in both link and actuator of the rigid-link robot system [64]. Herianto et al. [65] have been proposed a model and design of rehabilitation robot for assisting the patient to recover from stoke or other extremity injuries. The model that consists of two-link manipulator; link 1 assisted the knee and link 2 for the ankle was modeled into mathematical equation by using kinetic energy of motion and designed the PID controller with PWM input control. Based on the results, a system was successfully designed and manufactured.

Z. Taha et al. [66] the lower limb dynamics of the human limb and exoskeleton were modeled as rigid links based on the Lagrangian approach to derived the equation of motions for the nonlinear dynamic system and investigated the tracking performance of a robust control by a hybrid PD particle swarm optimized AFC. In another research, lower limb powered exoskeleton for ageing population has been developed. The dynamic model consists of two-rigid links robotic legs and the model was derived using Lagrange equation and the mathematical model successfully simulated in Simulink MATLAB software and then applied the PID controller. Based on the results show the robotic leg is able to move as dictated by the desired parameters by controlling the voltage supplied to the DC motors of the robotic leg [67].

4.4 Two-Link Flexible

Robot manipulators are an important research area, the advancement in the research of the manipulators is divided into two parts rigid manipulator and flexible manipulator. The current research is more inclined towards flexible manipulators because of their several advantages over rigid manipulators [68] [69]. The Flexible Manipulators (FMs) provide light weight, low energy consumption leading to low overall cost [70]. The advantages of flexible robot manipulators: have higher manipulation speed, can use smaller actuators, are more manoeuvrable and transportable, are safer to operate due to reduced inertia, higher payload to robot weight ratio [53]. The limitations of flexible manipulator include: control complexity because non minimum phase system, under actuation problem and non collocation. Uncertainties due to truncation of flexible modes, control spillover, observation spillover and eigenvalue problem. Multi Input Multi Output (MIMO) and nonlinear system [68].

The dynamical model of a flexible manipulator depends on the type of modeling method used. In the past three decades, many methodes have been developed for modeling flexible manipulators. There are serveral dynamic models of flexible manipulators ranging from the simple model such the lumped parameter method (LPM) to complex model such as the AMM and the Finite Element Method (FEM), Finite Difference Method (FDM) [71]. Different control techniques are developed based on type of the control problems such as proprtional-integral-derivative PID control technique [72]. Flexible manipulator is quite difficult to be accurately controlled by linear control approach due to their nonlinear dynamic structure [73]. Nonlinear control approach such as fuzzy logic control [74]. adaptive control [68]. Artificial Neural Network (ANN) based control [75]. Two-link flexible manipulators are more suitable in industry, in comparison with single link and multi-link FMs. Thus, it is interesting and important to present the extensive and exclusive review on different aspects of dynamical complexities, modeling, control problems and control techniques reported on two-link flexible manipulators [68].

4.5 Control Of Two Flexible Link

In this section there are some reviewed control strategy technigues that have been studied for two flexible link. Xiaoguang et al [76] established the PID controller with ANN feed-forward control for the vibration to suppress the two link manipulator movement in the planar also to control the trajectory tracking of the joint. The simulation results showed that, the tip trajectory of manipulator can be restrained the tracking and the vibration with a little error. A hybrid control scheme consists of non-collocated PID controller and neural network-based model predictive control for suppression vibration control and motion input tracking of the two link flexile robotic manipulator [50].

Cao Qingsong et al. [52] the optimal location of the actuator and sensor obtained for the two link flexible manipulator to suppress the vibration of the link and fuzzy self-tuning PID controller to suppresses effectively the vibration and the accurate location is obtained in the second link accurately. The authors developed the optimal boundary control based on the PDE system and apply the differential evolution equation to generate the optimal trajectory that can reduce the total energy consumption and then applied the control scheme to regulate the joint within the optimal trajectory and the suppress the vibration [77]. Jimoh et al illustrated a hybrid proportional integral derivative PID with iterative learning control of the two-link flexible manipulator for motion track and the vibration suppression. The authors reported that the PID-ILC control achieved the acceptable tracking with the former demonstrating better stability and energy efficiency [52].

Rasheedat M et al. developed an adaptive hybrid PD-PID control for the two-link flexible manipulator and very simple adaptation low used to turn the PD gains. The controller tested by using MATLAB/SIMULINK software [78]. Parida and Ranasingh [72] have been studied the assumed mode method and tracking control of a two-link flexible manipulator using PID controller. Chen et al. [79] have developed the position control of a 2 DOF (two-link flexible manipulator) in the active and passive joint. The position control using low chattering SMC techniques for position tracking and tip deflection control of the two link flexible manipulator is represented by Kshetrimayum and Binoy [80]. Hejia Gao et al have developed neural network control of the two-link flexible robotic manipulator using AMM and the PD to achieve the tip tracking control performance of the two flexible links and the neural network employed for a two flexible links to track the desired angular position trajectory. The authors emphasized that the neural network controller works better in vibration suppression [49].

Tahmina et al. [51] controlled the two-link flexible manipulator using algorithm (GA) based fuzzy logic controller for the input tracking and vibration reduction at end point of the two-link flexible manipulator. The developed the composite fuzzy logic schemes for flexible joint manipulator to tracking trajectory and the vibration suppression is presented by Mohd Ashraf Ahmad et al. [81]. In another research, studied on control the two-link flexible joint manipulators using PID controller to realize the tracking of the joint manipulator trajectory and improved the PID controller method for motion of the two-link flexible manipulator trajectory tracking. Based on the simulation results, this method has been proved the accuracy and efficiency [54].

5. Pid Controller

The most widely used form of industrial nowadays controller is the proportional-integral-derivative (PID) controller because simplicity, stability, low cost and effectives [82]. PID controller consists of three parameters which are illustrated in terms of time, while the proportional (*P*) depends on the current error, integral (*I*) depends on the deposition of past errors and the derivate (*D*) is the prediction of future errors.

The PID controller can be divided into parts, namely the PI and PD controllers. Meanwhile, the PI controller is form of phase-lag compensator and the PD controller is a form of phase-lead compensator. A PID controller is design the bridges based on the relation the proportional gain (Kp), the integral gain (Ki) and the derivative gain (Kd) as shown in Figure 7. The relationship is useful in the adjusting the value of PID parameters according to the response of closed system [83].

In recent years, many changed aspects of the PID controller design have been developed based on artificial intelligence technology in order to improve the performance of conventional PID [85]. The PID control technique have been widely used with other control techniques, such as Fuzzy Logic control for increasing the efficiency of the system. These two control techniques used in the combination between to improve the overall efficiency and system performance, as well as to get a more stable and reliable system [86]. Due to the flexible link manipulator has a natural characteristic which is it quite difficult to control the flexible mechanisms with conventional linear control method. The nonlinear control had a great advantage for analyzing the flexible manipulator systems, the reason that few PID controllers have been used to control flexible manipulators compared to the rigid manipulator systems [87]. PID controller is also said to be the most adopted controllers in industrial settings due to its relative ease of use and the satisfactory performance in a vast majority of processes [88].

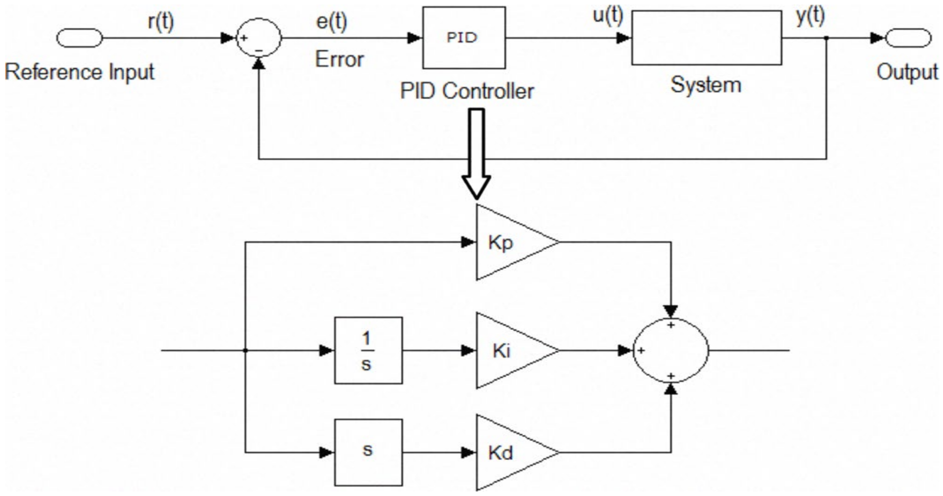


Fig. 7 *PID control scheme [82]*

6. Fuzzy Logic Control

Improvement of flexible link manipulator by using fuzzy logic control had been widely used for increasing the efficiency of the system. Due to the uncertain nonlinear system at flexible link manipulator, the fuzzy logic control is able to apply with universal approximate property [89]. Fuzzy logic control does not require a mathematical model to perform the controller system [90]. The fuzzy logic control is an analytical system by represented human way of thought process. It also does not require a sophisticated mathematical model control law [91].

The flexible link manipulator had a natural characteristic which is it quite difficult to control the flexible mechanisms with conventional linear control method. The nonlinear control had a great advantage for analyzing the flexible manipulator systems. The nonlinear control system can be divided into six group which is feedback linearization (computed torque control), passivity-based control, sliding mode control (variable structure control), artificial intelligence control, Lyapunov-based control and adaptive control [92].

7. Control Strategy of Existing Exoskeleton

There are a lot of different control strategies and approaches to regulate the powered augmentation exoskeleton systems as proposed by many researchers.

KIT-EXO-1, it utilizes the interaction forces acting in between the user's body and the exoskeleton as the input for the controller. The input is used to predict the upcoming motion of the user. The forces are collected using sensors attached at different part of the exoskeleton, especially at the knee joints [23]. Berkeley Lower Extremity

Exoskeleton (BLEEX) is mainly for enhancing the ability of human being by supplying the extra strength and force needed to carry certain payloads [93]. The control strategy of BLEEX is a mixture of position control for stance-leg and positive feedback based sensitivity amplification controller for the swing leg [67]. Moonwalker is a lower limb exoskeleton which is used for gait rehabilitation, locomotion assistance, and strength enhancing. The control of Moonwalker consists the how the wearer shares his reaction force on the ground between his legs and to drive the force sharing accordingly to distribute the balancer force between the two sticks in the same proportion by using three pressure sensors under each foot. The difference in reaction force exerted on each foot will cause the force-sharing device to tilt to either left or right to distribute the balancer [94].

HAL exoskeleton uses an autonomous control system that carries the user through predefined gait trajectories by controlling knee and hip joints and gait phase intention is estimated from COP/COG sensors. The second control strategy, a model-based approach for human strength augmentation, estimates human intention from EMG activity and provides power to augment torque that provided by the operator [95]. XoR is lower body exoskeleton that uses a hybrid pneumatic electric drive system. The control strategy is the Proportional Derivative (PD) feedback controller tracks desired joint angles and angular velocities that correspond to the state of the exoskeleton required to assist the human operator [96]. Hydraulic Lower Extremity Exoskeleton developed for military purpose, enhances mobility and reduces muscle fatigue. The control of the HLEE is based on the Dual-Mode control that comprised of an active mode in the stance phase and a passive mode in the swing phase. In the active mode, the exoskeleton is controlled to track the motion of the user and in the passive mode; its active joints start to work as passive joint by obstructive the hydraulic power supply from the hydraulic power unit. The transition control of the HLEE that consists of the torque shaping and the pre-transition algorithms that adopted to improve locomotion responses during gait phase transition [97].

The IHMC mobility assist exoskeleton is a robotic suit that the user can wear for strength augmentation or gait generation. The IHMC controlled based on the force control mode that actuator attempts to apply the torque equal to a desired torque and the position control mode that feedback controller is used to have the position of the joint track a desired position, for position control a PD controller is used to generate reference torque, which is used as the input to torque feedback controller [98]. The quasi-passive exoskeleton developed by Walsh demonstrated the need to match the user's joints and degrees of freedom in order allow for a natural gait. It also shows that a fully force controllable lower extremity prototype can be used to explore different active as well as passive based controllers [21].

HUALEX is human-powered augmentation lower exoskeleton that has been controlled based on an Adaptive Sensitivity Amplification Control (ASAC) strategy which provides the exoskeleton the ability to modify different pilot's dynamics in different walking speed and handle easily changing the interaction dynamics during normal walking then utilize a statistical method to estimate the trajectories by using a single accelerometer [99]. HEXAR is hanyang exoskeleton assistive robot developed for enhance lower body strength to enable human to carry heavy loads. The controller structure of HEXAR is composed of main controller, sensor control unit and motor control unit. The main controller to implement the control algorithm to obtain the sensor signal and sends commands to the joint actuator [100].

8. Types Of Actuators

Lower limb exoskeletons can be actuated by three types of actuators such as active actuation, passive or quasi passive assistive actuation, and hybrid actuation. Active actuators consist of electric, hydraulic and pneumatic actuators. Passive actuators comprise non-powered components such as springs, which can store energy based on the principle of gravity for balance. Quasi-passive actuators are passive device that work with viscosity devices such as dampers. Hybrid actuators are a combination of more than one type of active, active-passive actuators [101]. The exoskeleton could be extensively categorized into three groups according to their usage of the power, active exoskeletons which considered as powered exoskeleton, passive exoskeletons and passive-active exoskeletons [102]. Active actuation provides a power to the human gait cycle, usually through the motor such as DC motor and servo motor or hydraulic cylinders. The passive actuation does not require any energy source and consists of springs, dampers and linkages. Passive actuation is often lightweight, but because of their lack of power supply and electronics their controllability is limited [103].

Table 2 *Comparison between the actuators*

Actuator type	DC Motor	Hydraulic	Pneumatic
Advantages	- High speed control - Able to lift large loads - Easy to control - Full torque at zero speed - High efficiency	- High load capability - Able to hold large loads without sagging	- Low cost to purchase and operate - Energy storage - Accurate force feedback
Disadvantages	- High maintenance - Large and expensive - Not suitable in very clean environment - Low speed range	- Leaks oil - Requires excessive maintenance - Large and bulky - Expensive to purchase and operate	- Not accurate, uses fixed stops for positioning - Large cylinders required - Leak oil - Little holding power
Range of motion	Wide	Limited by the length of lead screw	Limited by the length of lead screw

9. Conclusion

This paper presents an extensive review of the major lower limb powered exoskeletons and develops a new lower limb powered exoskeleton that could benefit the people who engage in load carrying by increasing their load carrying capacity. Besides, there is a large patient population who suffer from multiple health issues leading to gait impairment. This paper convers various aspects of the two-flexible links in term of modeling method, dynamical analyses, and control approach to design lower limb powered-exoskeleton for carrying load with two-link flexible, in which the first link will resemble the femur while the second link will resemble the combination of tibia and fibula. This review summarizes the overview of augmenting exoskeletons, types of lower limb exoskeletons, biomechanics of human gait, the mathematical models of two-flexible link, and the control approach of the two-link flexible to generate flexible lower limb powered exoskeleton for carrying load based on the concept of two-link flexible.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

All authors equally contributed to this manuscript.

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