İLERİ MÜHENDİSLİK ÇALIŞMALARI VE TEKNOLOJİLERİ DERGİSİ

Robotic Design and Modeling of Medical Lower Extremity Exoskeletons

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Abstract

This study aims to explain the development of the robotic Lower Extremity Exoskeleton (LEE) systems between 1960 and 2019 in chronological order. The scans performed in the exoskeleton system's design have shown that a modeling program, such as AnyBody, and OpenSim, should be used first to observe the design and software animation, followed by the mechanical development of the system using sensors and motors. Also, the use of OpenSim and AnyBody musculoskeletal system software has been proven to play an essential role in designing the human-exoskeleton by eliminating the high costs and risks of the mechanical designs. Furthermore, these modeling systems can enable rapid optimization of the LEE design by detecting the forces and torques falling on the human muscles.

Keywords: Modeling, Exoskeleton, AnyBody, LEE, Rehabilitation.

Robotik Alt Ekstremite Dış İskeletlerin Modellenmesi ve Tasarımı

Özet

Bu çalışmanın amacı, 1960-2019 yılları arasında robotik Alt Ekstremite Dış İskelet (LEE) sistemlerinin gelişimini kronolojik sırayla açıklamaktır. Dış iskelet sisteminin tasarımında yapılan taramalar, öncelikle tasarım ve yazılım animasyonunu gözlemlemek için AnyBody ve OpenSim gibi bir modelleme programının kullanılması gerektiğini, ardından sensörler ve motorlar kullanılarak sistemin mekanik olarak geliştirilmesi gerektiğini göstermiştir. Ayrıca OpenSim ve AnyBody kas-iskelet sistemi yazılımlarının kullanımının, mekanik tasarımların yüksek maliyet ve risklerini ortadan kaldırarak insan-dış iskelet tasarımında önemli rol oynadığı kanıtlanmıştır. Ayrıca, bu modelleme sistemleri, insan kaslarına düşen kuvvetleri ve torkları tespit ederek LEE tasarımının hızlı optimizasyonunu sağlayabilir.

Anahtar Kelimeler: Modelleme, Dış iskelet, AnyBody, AEDİ, Rehabilitasyon.

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1. INTRODUCTION

In the world, many people lose their functionality of lower limbs and motor skills due to musculoskeletal diseases caused by either aging, such as in the elderly population or traffic accidents (O'Sullivan, Schmitz, & Fulk, 2019). Hence, many people need physical therapy to regain their lost motor skills and muscle functions. After the Second World War, mechanically designed exoskeleton systems have evolved towards mechanical designs with technology development. The Robotic exoskeleton system (RES) has been used to improve patient and rehabilitation (Calabrò et al., 2016). RES is used for medical purposes in patients and the military and industry for more comfortable transport of heavy loads by providing backbone support. However, this study focuses only on the design and modeling of RES for physical therapy.

Robotic LEE Systems (RLEES) are rehabilitation tools used to develop or recover walking ability in partial or total ability due to stroke, spinal cord injury (SCI), orthopedic, and neurological causes. With this robotic system, the neuronal pathway is activated to regain the nervous system (Louie, Eng, & Lam, 2015). The treatment's primary purpose is to mobilize the untreated lower extremities' normal distribution by providing support without causing any harmful side effects to the patients. The exoskeleton system plays an active role in gaining movement abilities such as standing, walking up the stairway, and climbing, especially in people with impaired mobility (Bogue, 2015; Federici, Meloni, Bracalenti, & De Filippis, 2015; Li et al., 2015; Nam et al., 2017; Riener, 2016).

The development of robotic exoskeleton has always been limited until the last 15 years due to being an expensive, lengthy, and complicated process. With the animation and computer-aided modeling programs such as OpenSim and AnyBody, these design processes and costs have been minimized in recent years(Agarwal, Narayanan, Lee, Mendel, & Krovi, 2010).

The rest of the paper is organized into five parts. The first part introduces the historical development and emphasized features of the RLEES designs. In the second part, the design similarities and differences between the robotic systems are discussed. The lower extremity muscle groups based on modeling and the simulation models are emphasized in the third part. In the fourth part, biomechanical analysis and design processes that are performed with modeling programs have been examined. In the last part, the modeling programs, the characteristics of the model designs that are designed today are examined, and predictions on the possible designs in the future are discussed.

2. THE DEVELOPMENTAL FEATURES OF ROBOTIC LEE SYSTEMS

The First LEE "Hardiman" was designed in 1960 for military purposes to balance the legs' load distribution. Medically, the first robotic exoskeleton system is the Lokomat developed by Hocoma (Figure 1). The Lokomat consists of a gait orthosis mounted on a treadmill and a weight support unit that supports it. Lokomat supports and assists the patient's walking by providing functional gait training, especially for lower extremity problems (Riener, 2016). The Lokomat with having a total of 4 degrees of freedom (DOF) has the necessary trigger mechanism to provide the patient with sufficient torque for linear motion in the hip, knee, and sagittal plane(Michaud, Cherni, Begon, Girardin-Vignola, & Roussel, 2017). The simulation programs and algorithms of Lokomat provide a virtual reality environment while the patient is walking and increases the patient's mobility(Wallard, Dietrich, Kerlirzin, & Bredin, 2015). Functional motion and sensory stimulation, controlled by computer commands, help patients to walk by synchronizing with the treadmill according to the typical walking pattern in patients with Multiple Sclerosis (MS) and Spinal Cord Injury (SCI) (Hussain, Jamwal, & Ghayesh, 2017; Sapiee, Marhaban, Ishak, & Miskon, 2018).

Figure 1. Lokomat gait rehabilitation robot (Riener, 2016).

Another medical robot is the Active Leg Exoskeleton (ALEX) gait rehabilitation robot, developed by Delaware University for patients having gait disabilities (Yan, Cempini, Oddo, & Vitiello, 2015).ALEX (Figure 2) is designed using a force field controller to move humans by the regular walking pattern in the desired trajectory. With seven degrees of freedom (DOF) points ((three in the waist joint, two in the hip joint (flexion/extension and abduction/adduction), one in the knee joint (flexion/extension) and one in the ankle (plantar / dorsiflexion)) ALEX has more DOF than Locomat. The sagittal plane's hip and knee joints move linearly with the actuators, while the wrist joints are passively designed with springs (B. Chen et al., 2016). The hip and knee joints are also equipped with force-torque sensors and encoders for feedback on human joints. ALEX is a clinically approved, exoskeleton gait system. It is used effectively in the rehabilitation of stroke patients. The human gait model and training are very close to an average persons' walking distance and speed. Thus, it provides safe and effective walking(Banala, Kim, Agrawal, & Scholz, 2008; J. Li et al., 2019).

Figure 2. ALEX III Gait Rehabilitation Robot (Stegall, Zanotto, & Agrawal, 2017).

Another gait assisting exoskeleton robot used in the lower extremity patients is the EksoGT device (Figure 3) developed by Ekso Bionics (Richmond, CA, USA). This exoskeleton robot is used to improve the mobility, strength, and endurance of patients with spinal cord injury, partial or complete loss of function in lower limb limbs due to stroke, traumatic brain injury, and MS (J. Li et al., 2019). Also, EksoGT is the first exoskeleton used in the treatment process of patients with stroke and approved by the US Food and Drug Commission (FDA)(Sirlantzis, Larsen, Kanumuru, & Oprea, 2019). EksoGT has a total of 6 DOFs, 3 DOFs per leg. Hip and knee DOF joints are actively designed to assist the patient in moving on the sagittal plane. In contrast, the ankle DOF joint was designed to be passive during the movement. For rehabilitation, the exoskeleton's support can be adjusted in parallel with the development of the patient. Clinically, EksoGT allows the patient to walk in a very similar way to a regular gait model of a healthy person by providing additional walking opportunities (Bionics, 2016).

Figure 3. EksoGT Lower Extremity Exoskeleton (Gardner, Potgieter, & Noble, 2017).

The use of LEEs for therapeutic purposes also includes the treatment of paraplegic patients. The first of these robots was the ReWalk exoskeleton (Figure 4), developed by ReWalk Robotics (Marlborough, MA, USA). ReWalk exoskeleton was developed to increase patients' health quality with Spinal Cord Injury (SCI) daily at home and in public areas. ReWalk exoskeleton allows people with SCI to coordinate healthy hip and knee movements to keep them standing and walking(Raab, Krakow, Tripp, & Jung, 2016). ReWalk is controlled by a computer program that receives signals from sensors, sensing the motion intention attached to the patients. It detects the self-initiated gait by sensing the upper body's forward inclination and imitate the natural walking pattern of a healthy person with a strong body(RANJITHA, 2019). According to the clinical study results of ReWalk LEE, paralyzed patients can practically stand up, which presents excellent opportunities for enabling patients with paralytic disorders to achieve substantial independence and restore their quality of life. These results also show that patients experience a reduction in secondary complications from wheelchair life, such as depression and neuropathic pain(Esquenazi, Talaty, Packel, & Saulino, 2012; Hartigan et al., 2015).

Figure 4. Sections of ReWalk LEE(Manns, Hurd, & Yang, 2019).

Another gait assisting exoskeleton is Vanderbilt, developed by Goldfad (Figure 5). It provides gait assistance to patients suffering from lower extremity problems. This exoskeleton was designed like a "Lego puzzle" as in it could easily be split into pieces and reassembled (Federici et al., 2015; Rupal, Singla, & Virk, 2016). This exoskeleton's weight is only 27 kg, but it can be used in patients up to 200 kg. The data from the sensors placed on the patient's hip and knee joints is evaluated with an embedded computer system, and the patient is allowed to perform repetitive movements with the actuators in the knee and hip(Gurvinder & Virk, 2016). Another feature of Vanderbilt is its functional electrical stimulation with robotic assisting. This feature allows the robot to work with the muscles while at the same time reducing the energy consumption as well as helping to heal the physiological wounds of the patient (Kirsch, Alibeji, Dicianno, & Sharma, 2016; Yan et al., 2015).

Figure 5. Vanderbilt Gait Assisting Exoskeleton.

CUHK-EXO LEE system, as shown in Figure 6 from Hong Kong University, is designed to help patients having paralysis to perform routine daily movements such as sitting, standing, and walking(B. Chen et al., 2018; Yan et al., 2015). CUHK-EKO LEE has a backpack, crutches, and a user interface. This exoskeleton's most important feature is that it has an anthropomorphic structure to provide maximum synchronization between user movement and robot joints mechanically(B. Chen et al., 2018; Liang et al., 2018). Another feature of this exoskeleton is that crutches use smart machine technology as part of human interaction. Sensor usage in crutches provides information about the patient's motion used to control the knee and hip actuator movements and establish the necessary angles(B. Chen et al., 2015).

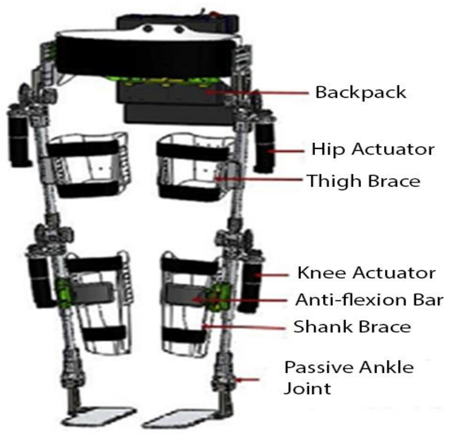

Figure 6. CUHK-EXO Exoskeleton (B. Chen, Zhong, et al., 2017).

Figure 7 displays the Hybrid Assistive Limb (HAL) is a wearable robot designed to rehabilitate patients with chronic physical disability in the lower extremity muscles due to a disease such as a stroke (Grasmücke, Cruciger, Meindl, Schildhauer, & Aach, 2017). While potentiometers are used to measure the joint angle, the ground response force sensors, gyroscope and accelerometer are used for a body posture assessment. Skin surface electromyography (SEMG) electrodes placed on the knee and the hip are used to predict the intended movement(Cha & Kim, 2018; Chinmilli, Redkar, Zhang, & Sugar, 2017). Also, HAL uses a control system that allows the user and the exoskeleton to synchronize their movements.

Figure 7. HAL exoskeleton (Jansen et al., 2018).

The Windwalker project organized by Twente University could be considered a new perspective in LEE designs (Figure 8). This exoskeleton design project consists of three main elements: Brain-Computer Interface (BCI), Virtual Reality, and mechanical design control (Mironov, Kastalskiy, Lobov, & Kazantsev, 2017). Mechanically, the MindWalker exoskeleton is equipped with support for flexion/extension and knee flexion/extension. These actuators are designed using the Series Elastic Actuating (SEA) principle, based on the muscles' anatomical features, allowing different control implementations and safe and compliant interactions with their surroundings (Y. Li et al., 2019). In this exoskeleton, an algorithm has been developed to determine the user-intended motion to assist weight shift and online-adaptation of the step width in maintaining balance. This algorithm works with smart sensors such as precision joint angle sensors, inertial measuring units (IMU), force/torque sensors, obstacle detection, etc. These sensors are connected to a network generated by the fast field bus system called EtherCAT (B. Chen, Zhao, Ma, Qin, & Liao, 2017; Ren, Deng, Zhao, & Li, 2018; Wang et al., 2014).

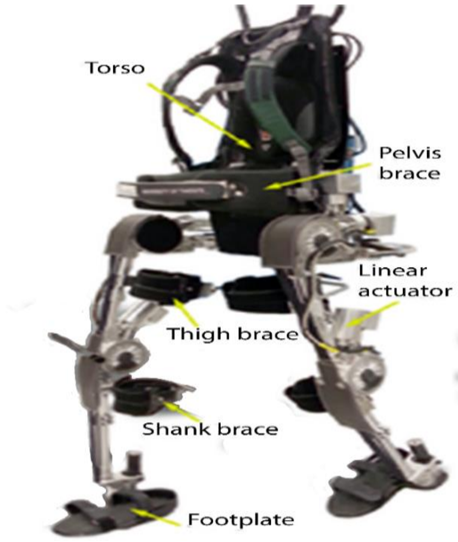

Figure 8. Prototype design of Mindwalker Exoskeleton (Wang et al., 2015).

3. SİMİLAR AND DİFFERENT ASPECTS OF LEE SYSTEMS

In recent years, the studies of all LEEs on the hip and knee joints, whether mechanical or robotic, are designed with dynamic movement capability where the ankle joint is designed as passive. LEE designs are aimed to support a balanced distribution of the load and aid the human backbone (Zhang et al., 2017). The mechanical parts design intends to ensure a balanced distribution of the load, thus reducing the weight and effort on the spine, joints, and muscles to the minimum (B. Chen, Zhong, et al., 2017; Meng et al., 2015). RLEE assisted gait training and treatment programs to aim to improve the patient's neuronal pathway activity by increasing muscle and joint activities. The robotic gait-assisted system is based on the human gait model, and therefore, the human gait analysis must be well studied. In gait analysis studies, EMG and joint freedom are analyzed by video and image processing. These methods are generally used to determine the movement and movement intention (Bulea, Lerner, & Damiano, 2018). It has recently been observed that EEG and EMG are used together to assess RLEEs (Crea et al., 2018). Artificial intelligence algorithms are applied to work following physiological and robotic applications(Haeberle et al., 2019; Ling, Yu, & Li, 2019). Additionally, utilized visual-virtual games enable patients to perform their movements without being clenched and increase their participation in the rehabilitation process(Mubin, Alnajjar, Jishtu, Alsinglawi, & Al Mahmud, 2019).

Table 1. Some commercial LEE's and their properties.

Exoskeleton Name	Usage Purpose	Actuated DOF	Actuator	Sensors	Specific Design Features
BLEXX (Agrawal, Dube, Kansara, Shah, & Sheth, 2016; Zoss, Kazerooni, & Chu, 2005)	**Human Strength Augmentation Gait Assistance**	**Hip Flexion/Extension Hip Abduction/Adduction Knee Flexion/Extension Ankle Flexion/Extension**	**Electric Motor**	**Force sensor**	**Body local area network Hybrid position and force controller**
HAL 5 (Shah, Mascarenhas, Menon, & Mengle, 2019; Yeung & Tong, 2018)	**Human Strength Augmentation Gait Rehabilitation**	**Hip Flexion/Extension Knee Flexion/Extension Shoulder Flexion/Extension Elbow Flexion/Extension**	**DC servo Motor Harmonic reducer**	**Plantar pressure sensor Angle sensor Gyroscope**	**Conscious recognition based on plantar pressure and torso angle**
HEXAR (W. Kim, Kim, Lim, Moon, & Han, 2017; Yeem, Heo, Kim, & Kwon, 2018)	**Human Strength Augmentation**	**Hip Flexion/Extension Knee Flexion/Extension**	**Electric Motor**	**Physical Human-Robot Interaction (pHRI) sensor Force sensor**	**pHRI-based control Quasi-anthropomorphic Active/Passive/Quasi-passive Joint**
LOKOMAT(Riener, 2016; Yue, Lin, Zhang, Qiu, & Cheng, 2018)	**Gait Rehabilitation**	**Hip Flexion/Extension Knee Flexion/Extension**	**Electric Motor**	**Position sensor Force Sensor**	**Bodyweight support system Visual feedback**
ROBOGAIT(Poberznik, 2018; van Hedel & Aurich, 2016)	**Gait Rehabilitation**	**Hip Flexion/Extension Knee Flexion/Extension**	**Electric Motor**	**Position sensor Force Sensor**	**Weight supported system Visual feedback**
ALEX (UNİVERSİTY OF DELEWARE-USA) (Jin, 2018; Nam et al., 2017)	**Gait Rehabilitation for stroke patients**	**Hip Flexion/Extension Knee Flexion/Extension**	**Linear Actuator (Max Torque:50Nm)**	**Encoder Force torque Footswitch sensor**	**Human-robot coordination**
EKSO BIONICS (Brenner, 2016)	**Human Strength Augmentation Gait Rehabilitation**	**Hip Flexion/Extension Knee Flexion/Extension**	**Electric Motor**	**Position sensor Force Sensor Pressure sensor**	**Microcomputer controlled algorithm**
REWALK(Neuhaus et al., 2011; Ortlieb, Bouri, & Bleuler, 2017)	**Human Locomotion Assistance**	**Hip Flexion/Extension Knee Flexion/Extension**	**Electric Motor**	**Position sensor Force Sensor Pressure sensor Internal senor**	**Windows operated computer Graphical user interface**
VANDERBILT (Murray & Goldfarb, 2012; Rupal et al., 2016)	**Human Locomotion Assistance**	**Hip Flexion/Extension Knee Flexion/Extension**	**Electric Motor**	**Position sensor Force Sensor**	**Low weight Functional electrical stimulation**

CUHK-EXO(B. Chen et al., 2018; B. Chen, Zhong, et al., 2017)	**Human Locomotion Assistance**	**Hip Flexion/Extension** **Knee Flexion/Extension**	**Electric Motor**	**Force sensing sensor** **Force sensor**	**Motion intention recognition** **PD controller** **Human-machine interface with mobile phone**

Although the designs mechanically are similar to each other, their sensor technologies and control algorithms are differentiated. Musculoskeletal modeling has gained importance in applying control algorithms and design features, which are expensive and time-consuming to be tested in real exoskeletal systems (Valente, Crimi, Vanella, Schileo, & Taddei, 2017). Therefore, the following sections are focused on the application of Musculoskeletal modeling in LEE modeling. Table 1 presents the commercially produced RLEEs, and Table 2 features the prototype RLEEs produced by universities.

Table 2. Types of LEE Designed in Universities.

Exoskeleton Name	**Usage Purpose**	**Actuated DOF**	**Actuator**	**Sensors**	**Specific Design Features**
Walking Assistance LEE **(Yonsei University of South Korea) (J.-H. Kim et al., 2015; Li et al., 2015)**	Patients with lower limb analysis	Hip Flexion/Extension Knee Flexion/Extension	200 W Brushless DC Motor, Harmonic reducer, Hip joint torque:79.3Nm, Knee joint torque:42.2Nm	Angle, Force, Plantar contact, and Inclonometer sensor	Cop Stability control Kinematic Analysis
IHMC Mobility Assist Exoskeleton (Florida Institute for Human and Machine Cognition - America) (Ansari, Atkeson, Choset, & Travers, 2015; Park, Lee, Shin, & Cho, 2015)	Paralysis patients for human locomotion assistance	Hip Flexion/Extension, Abduction/Adduction Knee Flexion/Extension	RSEA Mong BN34-25Eu-02 brushless motor, Harmonic reducer, Output Torque:80Nm	An optical rotary encoder, Linear encoder, Footswitch	Position control, Force/Torque control
Lower Limb Power-Assist Exoskeleton (Japan Saga University) (Li et al., 2015)	Lower extremity weakness for daily usage	Hip Flexion/Extension Knee Flexion/Extension	Maxon Dc motors	Encoder, Force, EMG, Laser Ranging, Plantar contact sensor	ZMP stability control Conscious EMG signal based control
Wearable Power Assist Locomotor (WPAL-Japan Nagoya University) (Fuse et al., 2019; Yatsuya et al., 2018)	Patient with lower limb analysis	Hip Flexion/Extension Knee Flexion/Extension Ankle dorsiflexion/plantar Flexion	DC Servo Motor	Three axes angular acceleration, Plantar pressure sensor Encoder	Swing phase Step trajectory Control of lower limb
ATLAS (Centre for automation and Robotics in Spain) (Cestari, Sanz-Merodio, Arevalo, & Garcia, 2014; Sanz-Merodio, Cestari, Arevalo, & Garcia, 2012)	Quadriplegic patients	Hip Flexion/Extension Knee Flexion/Extension	Brushless Maxon motors. Harmonic reducer, Peak torque;57Nm, Average Torque: 32Nm	Plantar pressure distribution sensor Angle Sensor	Cop stability Control, Conscious recognition

Lower Body Exoskeleton (University of Salford UK) (Costa & Caldwell, 2006)	Patients with lower-limb paralysis	Hip Flexion/Extension, Abduction/Adduction Knee Flexion/Extension Ankle dorsiFlexion/plantar Flexion	Pneumatic muscle actuator (pMAs), Torque:60 Nm	EMG sensor	The design of the actuator
Knee-Ankle-Foot Robot (National University of Singapore) (G. Chen, Salim, & Yu, 2015; G. Chen & Yu, 2014)	Rehabilitation robot	Knee Flexion/Extension Ankle dorsiFlexion/plantar Flexion	Maxon DC brushless motor, Harmonic reducer, screw nut, Maximum output torque:700N	EMG sensor, Angular sensor Force sensor Acceleration sensor	The design of the actuator Gait phase Classification
Ortholog (the Rio Grande do Sul Federal University-Brazil) (Roer, Abehsera, & Sagi, 2015)	Giat rehabilitation for Spinal cord injury patients	Hip Flexion/Extension Knee Flexion/Extension	24V/150WDC Motor Planetary gear reducer	Encoder	Brain wave control
Walking Supporting Exoskeleton(WSE((Necmettin Erbakan University-Turkey) (Önen, Botsalı, Kalyoncu, Şahin, & Tınkır, 2017)	Human walking assistance for Disabled People	Hip Flexion/Extension Knee Flexion/Extension	24V/100W DC Servo motor Reducer (100:1)	Plantar Pressure sensor Holzer effect sensor	Design of mechanical structure
Robotic Exoskeleton(Carlos III :University Spain) (González-Vargas, Ibáñez, Contreras-Vidal, Van der Kooij, & Pons, 2016)	Robotic walking assistance for Lower limb patients	Hip Flexion/Extension	Hip 24V/90W Maxon DC Motor	Inclinometer Force Sensor Imu Sensor	Trajectory Control

4. MODELING OF LEE ROBOTS

The design process of LEE robots includes hazards and risks due to the inability to fully understand the human-robot interaction(Skantze & Johansson, 2015). For this reason, the modeling of robots in terms of mechanical design and control mechanisms of LEEs is essential. Modeling enables the design of ergonomic systems to balance the load on the human body and the robotic garments' durability to be worn on humans.

The interaction between the musculoskeletal system and the exoskeleton's design needs to be well understood for maximum effect and minimum discomfort. For this purpose, many modeling programs such as MSC software, Freebody, Matlab, SimMechanics, Maplesim, AnyBody, and OpenSim are being used to perform dynamic analysis exoskeletons on the human neuromuscular structure. The most widely used modeling software with high-quality data production on humans' musculoskeletal system is the AnyBody Tech commercial software and Open-source OpenSim modeling software.

4.1. OpenSim Modelling Software

OpenSim is open-source software developed by Stanford University in 2007 and is a modeling program for the musculoskeletal system. This modeling program enables kinematic and dynamic analysis of gait and body movement(Khamar, Edrisi, & Zahiri, 2019). It enables new active and passive prostheses, such as new exoskeletons, based on the data analysis and model generation. An example of this is the study conducted by Baskar H et al.(2016) using OpenSim in which application of a LEE musculoskeletal model showed a reduction of torque and metabolic energy requirement for the hips, knees, and wrists during gait (Baskar & Nadaradjane, 2016; Mortensen & Merryweather, 2018).

4.2. AnyBody Modelling Software

The AnyBody modeling system is a commercial software offered by AnyBody Tech, enabling the analysis of human interaction with the external environment. AnyBody allows modeling of the lower limb, upper extremity, or the whole body in any desired size (Huysamen, Nugent, & O'Sullivan, 2014). In this way, kinematic and dynamic analysis of the person's walking and daily movements in the desired height and weight can be simulated (Díez et al., 2017). Also, the effects of joint-span, muscle strength, and torques, and human-exoskeleton interactions can be investigated. AnyBody Tech enables the design of ergonomic LEEs suitable for human skeletal structure through modeling according to the human musculoskeletal system. Access to previous exoskeleton models acts as a base and starts to design new exoskeletons (Zhou, Li, & Bai, 2017). An example of this is Fournier B. (2018) 's study, the modelling and characterization of a passive biomimetic ankle for a Lower Extremity Powered Exoskeleton (LEPE), defining requirements for a mechanical ankle design that can reduce crutch loads and thus extend the use of LEPE. In this study, it has been suggested that passive variable stiffness including second-order elastic spring elements for ankle using the existing exoskeletal and crutches models can be applied in the biomimetic ankle functions of the ankles and thus, the LEPE user will have increased vertical movement, control and reduced use of crutches(B. Fournier, 2018).

5. MODELLING AND BIOMECHANICAL ANALYSIS OF LEE

To examine an exoskeleton's physical behavior, it is necessary to perform kinematic and dynamic analysis and obtain a mathematical model. If the rotation of angle positions generated by the hip and knee joints during a single human walking cycle is identified, the actuator forces required to generate the walking movement can be calculated. As the exoskeleton is a system that assists in walking movements, the assisted movement is considered to be slow motion, and the dynamic loads are neglected. LEE models are generally based on the double pendulum system with 2 DOFs which are considered parallel to the exoskeleton. The free-body diagram representing the system is shown in Figure 9. l1 represents the thigh bone while l2 represents the calf bone. $\boldsymbol{\theta}_1$ shows the position in which the hip joint refers in the vertical direction, while θ_2 indicates the position of the knee joint relative to the thigh. The P1 and P2 show the variable lengths of the upper and lower actuators, respectively. It is possible to calculate the length of the two actuators as a function of the hip and knee angle positions. In particular, P2 is calculated using Equation 1.

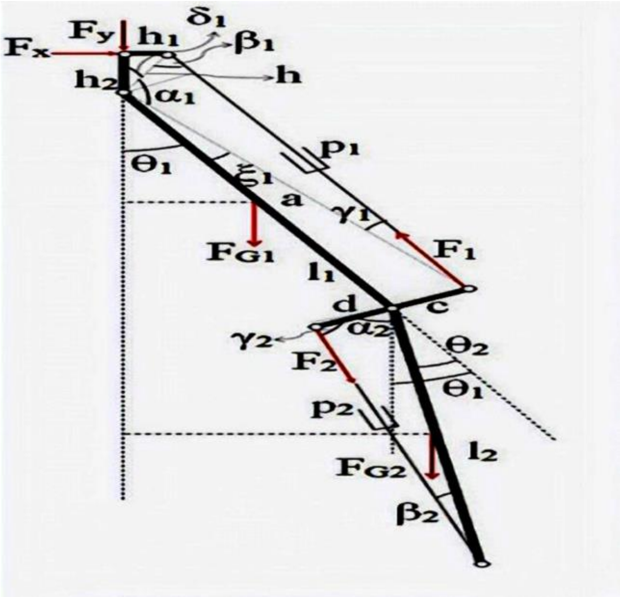

Figure 9. Kinematic structure of double DOF exoskeleton.

$$\begin{cases} \alpha_2 = \frac{\pi}{2} - \theta_2 \\ P_2 = \sqrt{l_2^2 + d^2 - 2l_2 d \cos\alpha_2} \end{cases} \quad \text{(Eq.1)}$$

On the other hand, P1 can be calculated as in Equation 2.

$$\begin{cases} \alpha = \sqrt{l_1^2 + c^2} \\ h = \sqrt{h_1^2 + h_2^2} \\ \xi_1 = \sin^{-1}\frac{c}{a} \\ \delta_1 = \sin^{-1}\frac{h_1}{h} \\ \alpha_1 = \pi - \theta_1 - \xi_1 - \delta_1 \\ P_1 = \sqrt{\alpha^2 + h^2 - 2ah\cos\alpha_1} \end{cases} \quad \text{(Eq.2)}$$

After calculating the actuators' length, other angles such as those between the upper and lower structures can be easily obtained using Equations 3 and 4, respectively.

$$\begin{cases} \beta_2 = \sin^{-1}(\frac{d}{P_2}\sin\alpha_2) \\ \gamma_2 = \pi - \alpha_2 - \beta_2 \end{cases} \quad \text{(Eq.3)}$$

$$\begin{cases} \beta_1 = \cos^{-1}\left(\frac{h^2 + p_1^2 - \alpha^2}{2hP_1}\right) \\ \gamma_1 = \pi - \alpha_1 - \beta_1 \end{cases} \quad \text{(Eq.4)}$$

F_{G1} and F_{G2}, taking into account the force motion system, the thigh and the Center of Mass (COM) represents forces resulting from gravity, F1 and F2 represent the upper and lower actuation forces. M1 and M2 are the approximate weights of the thigh and cavity sections applied to the COM, respectively. Tibia and femur forces, generated by the actuators, are calculated the balancing torque from a simple knee and hip center using Equations 5 and 6, respectively.

$$F_2 = \frac{m_2 g \frac{l_2}{2}\sin(\theta_1 - \theta_2)}{l_2 \sin\beta_2} \quad \text{(Eq.5)}$$

$$F_1 = \frac{m_1 g \frac{l_1}{2} \sin\theta_1 + m_2 g (l_1 \sin\theta_1 + \frac{l_2}{2} \sin(\theta_1 - \theta_2)}{h \sin\beta_1} \quad \text{(Eq.6)}$$

Equation 5 and 6 show how to achieve upper and lower actuator forces as a function of hip and knee angular positions θ_1 and θ_2 (Daines, 2019; Xinyi, Haoping, Yang, Zefeng, & Laurent, 2015). LEE modeling has been used to perform mechanical requirements and biomechanical analyses of human exoskeleton interactions. This provides convenience to the LEE designer in terms of both time and cost. Also, it allows the development of optimal LEE designs for muscles and joints (Arslan, Karabulut, Ortes, & Popovic, 2019). The literature's initial studies show that each leg and joint group's length is treated as a rotating joint of a body, and each joint is similar to a robot arm model. In these studies, joint angles and human movement can be considered as angular. Although such studies are known as skeletal models, they are considered as double pendulum models with simple two or three DOFs. Such models are often used to test and develop control algorithms with programs such as Matlab and SimMechanics (Ashkani, Maleki, & Jamshidi, 2017; Virk et al., 2016). The purpose of these control algorithms is to balance inertia and to provide users with low impedance, ensuring gait is performed with the least possible energy (Weerasingha, Withanage, Pragnathilaka, Ranaweera, & Gopura, 2018). In order to examine the effects of the exoskeleton on muscles and joints, the effects of extra weights and dimensions on joint angles are added to the musculoskeletal model with a three dimensional (3D) exoskeleton created by CAD software (Wu et al., 2019). Recently, 3D LEE models installed in musculoskeletal modeling programs such as AnyBody and OpenSim enable specific exoskeletal system designs for patients with distress and mobility problems due to their musculoskeletal system. (Lajeunesse, Routhier, Vincent, Lettre, & Michaud, 2018). Besides, with the development of new control paradigms, it is possible to design eliminate or minimize the negative effects of movements and related mechanisms that cause extra force on musculoskeletal system, such as walking, sitting, jumping, rope jumping, etc.

Studies on LEE model designs according to the human muscle model and their effects have started in recent years. One of these studies investigates the lower extremities model's effect on the musculoskeletal model on OpenSim conducted by Ferrari et al.(2008) (Ferrari et al., 2008). In this study, joint and joint angles were analyzed dynamically by biomechanical analysis during normal gait with and without LEE. However, the lack of ground reaction force and ground contact model analysis in the study decreased the results' accuracy. In the study conducted by Xu et al. (2019), RLEE design with Magnetorheological Actuators was analyzed using the AnyBody modeling program. The system is operated in two modes: robot and active human mode. Inactive robot mode, it is seen that RLEE provides adjustable torque and reduces power consumption compared to the active human model(Xu et al., 2019). The study was conducted by B. N. Fournier et al. (2018) designed two RLEE models, SCI and biomimetic. It was observed that the biomimetic model could be used in RLEE designs to reduce crutch requirement and optimization of the SCI model to provide more effective walking with a crutch (B. N. Fournier, Lemaire, Smith, & Doumit, 2018). In the study of Cho. et al. (2012), the effects of load-lifting movement on the joint forces were examined on the human-skeleton model developed with two constraints. The use of the strap on these effects reduces the user's comfort and states that it places an additional load on the joints when not in use. However, it was stated that the load distributed should be balanced using the wide belt(Cho, Kim, Yi, Jung, & Lee, 2012).

In the recent exoskeleton design simulations, there is a force called ground reaction force (GRF). The ground reaction force is a force applied to the ground by an object in contact with the ground. The ground reaction force is divided into two; vertical and horizontal force. The vertical ground reaction force can be used to examine the effects of loading effects and walking mechanics of the reinforced exoskeleton assisted gait at a different weight, walking speed, and support levels.

5.1. Human Gait and Biomechanical Effects

Human gait is a result of complex muscle movements. Human gait can be defined as the locomotion achieved through human limbs that change the subject's position from the previous position. The human gait is considered as a set of movements consisting of certain phases with the same cycle. When the walking cycle is considered, it consists mainly of two phases, single and double support phase. The single-phase is where one foot is in contact with the ground, and the other is in the swinging position and the air. The double support phase is when one foot is standing on the ground, and the other standing foot leaves the ground. In human gait, only one foot is in contact with the ground. Thus, it differs from running in this way.

If the human walk begins with the right leg, the first leg moved from the human's vertical position is the right leg, moving forward then put on the ground. The first stationary walking step includes the left leg's placement at the set position, which provides a single left leg and foot support until the right leg movement is completed. The second gait step is similar to the first gait step, but this step has one leg support, the left leg, until the right leg is lifted and placed back on the ground. Repeating continuous walking steps causes a continuous movement in the sagittal plane. As shown in Figure 10, the gait cycle consists of 8 states; 5 motion in the stance phase and 3 in the swing phases (Alamdari & Krovi, 2017).

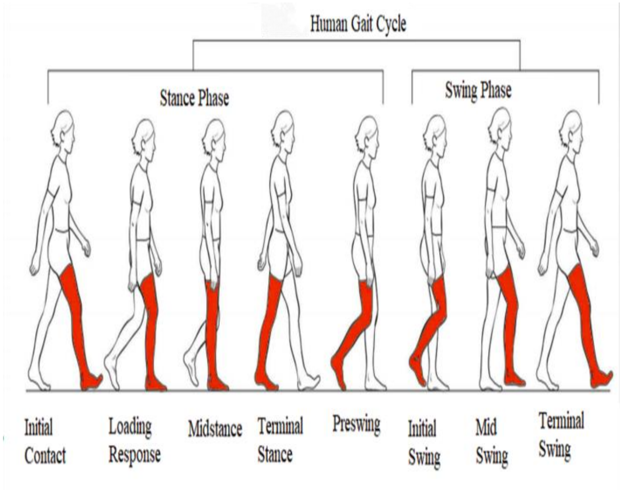

Figure 10. Human Gait Cycle.

A gait cycle is described as a percentage rather than the elapsed time. In this case, one step was expressed as a hundred degrees, the Heel Strike (HS) was 0%, and the location of the same foot to the ground was determined as 100%. During the normal gait cycle, the hip, knee, and ankle joints are subject to a series of movements. Hip motion can be considered as a combination of two basic movements. First is the horizontal balance of the hip that occurs in the stance phase and has a primary role in keeping the body in balance, while the second is hip Flexion during the swing phase. During the stance phase, the knee is the primary determinant of limb stability, and knee flexibility in the release phase is the main factor in the freedom of the extremity. At average walking speed, each double support period is about 22% of the walking cycle and is generally accepted as 20%. In mid-standing, the total body weight is transferred to the stretching knee. The ankle motion range is not substantial but is critical to progression and shock absorption during stance. The body is supported on a single limb throughout 80% of the gait cycle.

While walking, the body's mass center rises to its highest point in the middle stance when one foot passes vertically and then falls to its lowest point by the separation of the legs. Essentially, kinetic and potential energy are continuously exchanged in this process. A reverse dynamic analysis should be performed to determine the required torque/force in each joint during gait. For this purpose, kinetic data and external forces obtained from the visual sensors should be recorded during the experiment. The GRF is the main force acting on the body during human movements. Since the mass body moves in three directions, a three-dimensional force vector, consisting of vertical and two horizontal sectional constituents, moves on the contact area. These horizontal forces are usually divided into anterior-posterior and medial-lateral directions. These forces are small compared to the vertical GRF. The vertical GRF will be zero at the time of contact with the ground during HS and will gradually rise almost in a fraction of a second against the body weight. In the footplate, the body mass moves downwards and extends down on the leg. It is necessary to apply a vertical force more significant than the bodyweight on foot to slow down the movement and support the body weight. It shows 120% of the bodyweight applied to the foot at this moment for the subject. In the middle stance, the movement of the body's center of mass is upward. This movement creates an upward acceleration that allows a force less than bodyweight to support the body. At this moment, it shows 63% of the body weight in the middle. In the heel, the body mass accelerates forward and upward for the other leg's stance phase. This means the extra weight is applied to the bodyweight to support the body. Finally, the last swing is when contact with the ground is lost, and the force returns to zero. During the stance phase, the foot forces move in the forward and backward position as the body stops and then moves more quickly in the forward direction. Consequently, it can assume that the resultant force passes through the center of gravity of the entire body in motion(Alamdari & Krovi, 2017).

6. DISCUSSION

A mechanical or robotic exoskeleton is designed for three purposes. First, the mechanical design distributes the load in a balanced way to apply the least possible load force on the joints and muscles. Second, mechanical designs strengthen the muscles with neuronal pathway activity stimulation by rotating the joints at certain angles in patients with insufficient muscle strength and spinal cord injury. Finally, it is aimed to control the walking movement of patients initiated by biological signals such as Electromyogram (EMG) or Electroencephalogram (EEG), therefore rehabilitating the patient and improving the quality of life and socialization.

LEE designs focus on two areas: mechanics and software. In mechanical designs, comfort, reduced equipment weight, resistance, extended service life, and contact surface come to the fore. In software design studies, fast and effective control algorithms, systems that process and evaluate information from sensors are studied predominantly.

Modeling plays an essential role in LEE designing, as this process is considered expensive and complicated. For testing the developed control algorithms, modeling programs such as SimMechanics and Maplesim are used. However, musculoskeletal modeling programs such as OpenSim and AnyBody are used to perform human-exoskeletal interactions and kinematic analyses. By analyzing the walking kinematics, the body segments and length should be carefully designed using joint force and moment. Another result obtained in the kinematic analysis is the increase in muscle force applied to the ground as the muscle strength increases. This ground reaction force can be calculated by programs using inverse kinematic calculations in a similar way to reality. Although the inverse kinematic method enables us to calculate the GRF, it is still impossible to calculate the segmental analysis's ground loading effects.

In musculoskeletal models such as AnyBody and OpenSim, Videos and EMG signals were analyzed to determine the effects and optimal gait activities. Thus, the effects of LEE designs and gait activities on the muscles and nervous system were investigated. In AnyBody and OpenSim designs, muscles that are not or weakly functioning can be exercised while the force and torque on the joints and muscles and their effects on the joint angles can be calculated in patients suffering from SCI and stroke. In this way, LEE designs can be realized to reduce the minimum weight on the troubled muscles and joints during human gait.

LEE designs aim to develop torque control algorithms and to test them on models. By examining and comparing the integrating forces between the exoskeleton and user, the control mechanism's reduction effects on user loads, such as on joint torques, reaction forces, and muscle activations, can be examined.

7. CONCLUSIONS

To date, studies on the design of LEEs have focused on ergonomics and comfort or on the control of joint motors with appropriate control algorithms. Since this procedure is generally expensive and has certain risks for patients, three-dimensional geometric models of the lower extremities have been created and dressed on musculoskeletal models to minimize these procedures' risks. Above mentioned studies focus on the torque-forces and motion range of the muscles and joints following the gait pattern. Although the number of musculoskeletal models on some disease characteristics is very few, some restricted or disabled muscles and the effect of muscle deficiency or deficiencies on gait and muscles have been investigated. Besides, actual walking and muscle strength measurements and range of motion were obtained through cameras and sensors, and software and algorithms have significantly improved these measurements' quality. Future works will conceivably include a process of coordination with artificial intelligence, sensors, and programming. In further studies, exoskeletal model designs involving human exoskeletal interaction can be continued by modeling six muscles in the lower extremity and other muscles. With artificial intelligence algorithms, where ground reaction force is sufficient, less force and torque will be applied to muscle groups.

DECLARATIONS

Conflict of Interest: The authors declare that they have no conflict of interest.

Ethical Approve: This chapter does not contain any studies with human participants or animals performed by any of the authors. The data used in the study were obtained from the UCI Machine Learning Repository database.

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