Materials Today: Proceedings 44 (2021) 4251–4255

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

A systematic review on gait analysis methods and assistive devices in lower limb prosthetics

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ARTICLE INFO

Article history:
Received 5 October 2020
Received in revised form 13 October 2020
Accepted 19 October 2020
Available online 30 November 2020

Keywords:
Lower limb amputation
Prosthesis
Gait analysis
Gait assistive devices

ABSTRACT

In recent years there is a high demand for assistive devices for the lower limb amputees. Assistive devices play a major role in rehabilitation post prosthesis globally due to problems associated with the prosthesis. This literature research aims to find out an affordable, accessible, and easy to adapt assistive devices for lower limb amputees to analyze gait cycle post prosthesis. The performance of different techniques used to analyze the walking patterns of patients having lower limb amputations by the previous researchers is presented. The efforts made by healthcare professionals in developing rehabilitation duration and prognostics are also identified. A structured review of the literature of the rehabilitation, assistive devices used is carried out. The various methods for the synthesis of planar single and multi-loop linkages along with the methods for defect-rectification are explored. This review addresses the gait analysis methods and assistive devices in lower limb prosthetics systematically and thoroughly.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Advances in Materials Processing & Manufacturing Applications.

1. Introduction

Aging is a natural process that can be seen around the world. It changes the body composition, muscle strength, and reduces the capacity to perform routine activities efficiently. Furthermore, the elderly are more prone to diseases such as strokes, arthritis, central nervous system disorder, etc. According to the *Indian Aging Report 2017*, arthritis and stroke cases amongst the elderly may increase up to 55.9 million and 1.9 million, respectively, by 2030. These diseases may cause severe knee pain, gait deviation, abnormal mobility, and debilitate lower limb. To provide relief to the patients, case-specific measures are taken such as manual physical therapy, use of robotic rehabilitation device/exoskeleton, supporting device/brace, etc.

The manual physical therapy is helpful for the patients to regain control over the lost functions. However, it is laborious and backbreaker for both the patients & the therapists. Besides, irregularities in the training sessions may not recover the patients' ambulation and lost functions. Moreover, the therapy is not optimal because training time is limited and gait trajectories of the patients are not reproducible.

The robotic exoskeletons/rehabilitation devices help the therapists to engage with patients, intervening in the therapy, and assessing the outcome of the therapy. Also, it provides active and repetitive movements in a controlled manner that helps the patients in recovering ambulation [1]. In these devices, actuators are attached to the legs of the patient which provide the required motion. Furthermore, that systems may include the hip and the knee degree of freedoms for providing motion to the patient's foot [2]. However, there are limitations in some rehabilitation devices such as they are bulky, complex, and expensive. Besides, they operate in confined areas and special training is necessary to operate that makes them less amiable to therapists and small clinics.

The exoskeletons/devices are categorized as, treadmill-based, portable lower-limb, and over-ground rehabilitation devices, according to their type functions. The over-ground and portable rehabilitation robots include mechanical braces and computer-controlled actuators that allow the patients to experience realistic walking. However, a portable exoskeleton requires crutches for

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https://doi.org/10.1016/j.matpr.2020.10.541
2214-7853/
Selection and peer-review under responsibility of the scientific committee of the International Conference on Advances in Materials Processing & Manufacturing Applications.

balancing. As opposed, treadmill based-exoskeletons require a body-weight support system for balancing while this literature survey was aimed to study of gait monitoring methods and assistive devices used in analysis of gait lower limb amputees.

2. Treadmill-Based gait monitoring

The treadmill-based gait monitoring system contain a body-weight system (BWS), a treadmill, and a leg orthosis. This type of system is also known as immobile robots. They allow gait training in confined areas. However, they are considered effective in gait recovery because they reduce gravitational forces on the legs [3,4]. Various treadmill-based exoskeletons have been explored over the years. Typically, these are multi-degree of freedom devices that contain mechanisms, actuators, and control technology for manipulating users' lower limb motion while walking. Some of the treadmill-based rehabilitation devices are discussed here. The ReoAmbulatorTM is commercialized by Motorika USA Inc. and powered to lift a patient from a wheelchair and transports the patient over the treadmill [5]. Lokomat is created a prototype of driven walking pattern orthosis and is aided with a image processing environment along with visual biofeedback and audio which is available commercially [6]. The driven gait orthosis is a treadmill-based exoskeleton that actuates hip and knee, while the parallelogram linkage is used as an attachment for the trunk. The setup with parallelogram linkage allows controlled movement of legs in the sagittal plane, and it does not restrict the patients to keep their trunk in a vertical position themselves [7].

Besides, it utilizes a revolute joint between the thigh and lower leg attachments to allow the anterior-posterior motion of the leg. The LokoHelp is another treadmill-based system that is fixed onto the powered treadmill to transmit the motion to the levers positioned on its both sides. These levers imitate the swing and the stance phases in the desired manner and naturally guide the walking movement. Also, it consists of BWS located over the device, and orthosis which are attached to the levers. The ALEX (Active leg exoskeleton) is another gait assistive device that consists of a walker, thigh segment, shank segment, trunk orthosis and foot segment. Herein shank segment maintains one degree of freedom (DOF) concerning the thigh segment while walking. A force field controller is used for assisting the patients and linear actuators are used at the hip and the knee joints [8,9].

The LOPES (Lower extremity powered exoskeleton) exoskeleton is also used for assisting gait which contains two rotational actuated joints one at the knee joint and another at the hip joint. In this exoskeleton, no supplementary DOF or motion ranges are required to track the amputee's motion because this assistive system moves parallel to the legs of the patient [10]. The LOPES exoskeleton wherein thigh and shank segments are connected by a revolute joint. The Pelvic Assist Manipulator (PAM) controls natural pelvic motion, and the Pneumatically Operated Gait Orthosis (POGO) which is attached to PAM uses linear actuators to move the patient's pelvis and legs for training over the treadmill [11]. In contrast, a compliant robotic orthosis developed at the University of Auckland used a pneumatic muscle actuator to power the knee and hip joints in the sagittal plane. Besides, the orthosis allows both lateral and vertical translations of the trunk through passive mechanisms. Like other exoskeletons, this orthosis also uses a revolute joint for knee flexion and extension in the sagittal plane [12]. The robotic gait rehabilitation systems are also developed for patients suffering from hemiplegia. This system supports the torque of the weak limb of the patient. The robotic gait rehabilitation system that has actuated knee and hip joints. Also, the system has 3 DOFs for each leg; the revolute joint is considered at the knee of the system [13].

These treadmill-based gait rehabilitation systems have a multi-degree of freedom; however, they have knee with a single-axis revolute joint that allows only rotational motion. So, to select the best mechanism, it is essential to comprehend the bio-movements of the knee joint and its togetherness with the hip and ankle joints [3]. Besides, the mechanisms for these devices are designed using the 'tear-drop' trajectory in which the hip joint is considered stationary. As opposed to these exoskeletons, the UCI (University of California, Irvin) gait mechanism [14–16], and NJIT gait rehabilitation system [17], have six- and four-bar linkages, respectively, which are utilized for the whole limb. Also, the treadmill-based exoskeletons are bulky, and they are often used in rehabilitation centers and hospitals. The other categories of exoskeletons are over-ground and portable exoskeletons.

3. Mobile base Over-Ground gait monitoring

The mobile base over-ground rehabilitation exoskeletons may consist of a mobile base, a BWS, and joint level assistance to provide comfort to the patients for rehabilitation. They do not restrict training to the treadmill or a confined area rather they allow patients to regain their natural walk. In addition, the patients move voluntarily despite considering a predetermined pattern for moving. Some of the over-ground exoskeletons are explored to identify the mechanism used for the joints.

Exoskeleton for patients and the old by the Sogang University (EXPOS) is developed by Sogang University, especially for the elderly and the patients. It is an over-ground exoskeleton that contains a caster walker for balancing during rehabilitation training. It is a multi-DOF device that uses four actuators for driving the wheels of the caster walker to aid the patient's motion; while the hip and knee joints are actively assisted by servo motor controls and ankle joint is passively assisted by shock absorbers. The device pneumatically actuates the handle of a caster walker for synchronizing the up and down motions during walking on the leveled ground. Moreover, the EXPOS have air bladders that are wrapped by the braces and attached to the muscle. The pressure sensors are attached to those braces for measuring any change in the pressure of the air bladder with the muscle movement [18]. SUBAR (Sogang University biomedical assistive robot), may also be used for over-ground rehabilitation which is a version of the EXPOS. This version of the exoskeleton has improved transmission mechanism and actuating power for providing effective assistance [19]. LEER (Lower Extremity Exoskeleton Robot), NatTURe-gaits, WalkTrainerTM, and Kine Assist robotic device are among other rehabilitation devices that may also be used.

The LEER device was developed by a group of researchers at Shanghai Jiao Tong University in China. The device contains a mobile platform and embedded with powered knee and hip joints in orthosis. The joint's movement in the device is assisted by force provided by the exoskeleton which also assists the weaker muscle to complete the desired movement [20]. This device also uses revolute joints at the knee and ankle. Another exoskeleton with the mobile platform NaTure-gaits (natural and tunable rehabilitation gait system) can also be used. One of its notable features is, it provides 6 DOF for assisting pelvic motion which is important in clinical rehabilitation [21]. The same feature is observed in WalkTrainerTM developed at Laboratoire des Systemes Robotiques (Ecole Polytechnique Federale de Lausanne) for gait rehabilitation. The system contains a deambulatory, a BWS, a pelvis orthosis, electro stimulator, and two leg orthoses. Besides, the thigh and leg segments are connected through the revolute joint, and the ankle joint is actuated through a powered parallelogram mechanism [22]. A gait analysis method based on 4-bar linkage is also proposed by sigh R. et. al. [23] to find out gait trajectories by taking it in a global reference frame.

KineAssist may also be used for rehabilitation that contains a trunk and pelvis mechanism for allowing the natural walk and balance exercises [24]. A compact mobile lower limb robotic gait assistive system (MLLRE) [7] and gait trainer (LGT) are among other mobile exoskeletons that use linkage mechanisms at joints and lower limbs, respectively. The linkage mechanism used in MLLRE utilizes a mechanism based on slider-crank for actuating the hip and knee joints [25]. In contrast, a passive linkage mechanism can also be used for the whole lower limb in the caster walker to rehabilitate gait [26].

It is found that the over-ground exoskeletons with mobile bases have multi DOFs, and a single-axis revolute joint is used between the thigh and lower leg segments of the exoskeleton. Further, in some of the devices, robotic orthosis provide motion to ankle, knee and joints in the sagittal plane; while some exoskeletons use a linkage mechanism for actuating joints. The linkages are synthesized based on the "teardrop" trajectory which is obtained by making the hip joint stationary.

4. Portable gait monitoring

These systems are mobile and do not require any base or treadmill. As opposed to treadmill-based gait monitoring system, they are lightweight and easy to don and doff. Their simple and small structure makes them relatively more comfortable in comparison with treadmill-based and mobile-based over-ground analysis system. Besides, one of the most notable features of the portable exoskeletons is that they allow natural walking, and the power source is attached to the exoskeleton for actuating the joints. Besides, the users require crutches along with the exoskeleton during walking because of their impaired physical ability. Some of these portable multi-DOF exoskeletons are explored here.

ReWalk, Indego, and HAL are some of the commercially available portable systems that can be used with crutches for rehabilitation. The ReWalkTM exoskeleton is developed by ReWalk Robotics Inc., for paralyzed patients to assist them in standing and walking. It contains motorized joints, a rechargeable battery, sensors to measure the joint angle, ground contact, etc., and a backpack comprised of the control system. The device has bilateral thigh and leg segments that are hinged at the knee [27]. Another commercialized analysis system developed at Vanderbilt University can also be used for treating paralyzed patients. It consists a control structure controlled joint-levels. Moreover, the knee joints and hip joint are powered by direct current actuators, and brakes are included as a safety measure. The gait analysis system is proposed to use with forearm crutches for stability [28,29]. A single leg version of a hybrid assistive limb (HAL)[17] may be used for the patients of hemiplegia. The exoskeleton of the HAL in which the hip, knee, and ankle joints have single-axis joints in the sagittal plane [30]. Linkage mechanisms, for actuating the knee and hip joints, can be incorporated in the robotic orthosis for improving the gait speed, step length, and dynamic cosmoses of walking [31].

The modified form of the advanced reciprocating gait orthosis (AGRO) which uses a linear actuator, at the knee joint, to construct a four-bar mechanism and the same mechanism is used at the hip joint for actuation. This makes it a two DOF robotic orthosis. However, a single DOF mechanism may be used to actuate hip and knee, simultaneously. The four-bar mechanism can be used to actuate the hip joint which in turn actuates the knee joint through a cam modulated mechanism [32]. The motion can be achieved in the sagittal plane using revolute joints as a connection between the thigh and lower leg segments. Besides, a complaint a number of elastic actuator can also be used for actuating the knee and ankle Various portable gait rehabilitation devices have been explored and it is observed that the revolute joint is used to join the thigh and leg segments. The exoskeletons reported in this section have multi DOFs, however, only PGO is found to have a single DOF for actuating hip and knee simultaneously. Linkage system play a major role in the actuation of mechanism, gait speed, step length, etc. [2]

5. Assistive devices

It is worthwhile to investigate the area of assistive devices or orthosis for lower limb while analyzing for gait rehabilitation. The orthosis is an externally applied device which is used to modify the structural and functional characteristics of the skeletal systems as guided by International Organization for Standardization (ISO). Typically, it is used to alter the gait deviations of amputees. Restraining joint mobility, assistance in ambulation, stability, correcting limb malformations are some of the important features of an orthosis [33]. Various orthosis that are used for altering gait pattern are explored. The knee brace use a three-point fixation system, to effectively control hyperextension and avoid hyperextension. An off-the-shelf knee brace having a hinge between shank and the thigh which can be used by the osteoarthritis patients [34]. A principal feature of the hinged knee brace is to control flexion and extension of the leg. A revolute joint between the thigh and shank segments, or it can also be a double gear mechanism, that can imitate the rotary movement of the synovial knee joint naturally [35]. Another orthosis that can be used for providing relief to osteoarthritis patients can be an adjustable unloader knee brace which uses a polycentric joint between thigh and leg segments. In addition, this novel knee brace does not require straps for providing the needed moment [36].

Besides, the orthosis can be extended to the ankle, and foot and those types of orthosis are called knee-ankle–foot orthosis (KAFO) [29]. A KAFO with a cam mechanism with friction rings and lock that enable the KAFO to lock the knee joint at any position to assist the patients with knee flexion contractures [37]. The gait assistive devices may be embedded with the linkage and other mechanisms to imitate the behavior of human lower-limb.[38]

Another KAFO uses a four-bar linkage for coupling the knee and ankle movement [39].Other types of KAFO use motors or actuators at the knee and ankle joints, for example, Robot KAFO, KAFO with an actuator, exoskeleton with 4-bar linkage actuator, etc. A Robot KAFO in which an accelerometer at the hip joint identifies the gait phase and the actuator at the knee joint generates the torque required for assistance [40] whereas KAFO with actuator uses a four-bar linkage for actuating the knee joint, the linkage is formed by two steel cables, a metal bar [20]. Also, actuators with linkage mechanism at the knee joints are found. A four-bar linkage actuator for knee assisting device that can be used to mimic the motion of the knee joint for the rehabilitation of hemiplegic patients [41].

In the assisting device for knee joint, came mechanisms, single-axis joints and gear are used. Many researchers worked on the devices in which the linkage mechanisms for actuation and linkage mechanisms for to couple the knee and ankle movement are used. Besides, exoskeletons and assistive devices, it is equally important to investigate the linkage mechanisms used in walking robots. In the functioning of the assistive and exoskeleton devices, the mechanism plays a vital role and mechanism can also be used in rehabilitation devices and bipeds for the benefits of the society. For studying normal and pathological gait biomechanics, computational analysis and motion capture techniques with musculoskeletal modeling are the most using tools. There are only few techniques are available for gait analysis in the patient who are using prosthesis due to lower limb loss. Due the inability to place tracking markers on residuum the motion and associated loadings are not captured while there is a considerable motion in the residual limb [42–47]. Motion at the residuum socket interface can be the reason of changes in effective length of the single modeled segment. The speed in the residuum-socket interface that varies over the gait cycle and varies between subjects will cause a change in the effective length of a single model segment running from knee to ankle [48]. However, the residuum-socket interface, regardless of the motion at which it exists, is generally considered rigid, in the study of dynamics simulations [49]. The residuum-socket interface presents challenges when using traditional marker-based kinematic techniques otherwise the it can be explicitly treated as another joint in the system. Direct methods that determine gait kinematics effectively treat residues and prostheses socket/archway as a segment have been studied by previous researchers on the people who walks using prosthesis [50]. Researchers have been developed and used various sensing technologies including custom proximity sensors, radiography, fluoroscopy to sort out the problems of not measuring the loading while the motion is present at the residuum socket in experimental data [51–54]. Lu and O'Connor first suggested that that current marker-based IK methods predict conditions and estimates of all underlying body segments, [55–56]. Seth A. et. al. [57] developed and presented a model with the help of OpenSim for patients with unilateral transtibial amputation.

6. 6.Conclusion

Different techniques of gait analysis of lower limb amputees are introduced and the types of the assistive device are discussed. Finally the long term developments in the prosthetics engineering and visions for user's needs and experiences are presented. On the basis of review of the literature we can conclude that the assistive devices must be easy to operate, portable, less time consuming, have more degree of freedom and should be capable to analyze dorsiflexion, planter flexion, eversion and aversion simultaneously. This systematic review will help researchers to compare, choose and develop the best suitable gait analysis method for their field of research.

CRediT authorship contribution statement

Radheshyam Rathor: Conceptualization, Methodology, Writing - original draft, Resources, Data curation, Software, Validation, Investigation, Formal analysis. **Amit Kumar Singh:** Supervision, Writing - review & editing. **Himanshu Choudhary:** Formal analysis, Writing - review & editing. **Chandramani Goswami:** Writing - original draft, Resources, Conceptualization, Methodology. **Gusztáv Fekete:** Formal analysis, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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