

Review of Control Strategies in Lower Extremity Exoskeleton

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Abstract

Personal mobility is one of the biggest challenges for ensuring the quality of rehabilitation in the lives of Persons with Locomotor Disabilities (PwLDs) and old aged persons. In order to ensure effective orthotic rehabilitation, there is need to design and develop more and more automated aids and appliances. In order to know the status of research a study has been made on the controllers of lower limb exoskeleton (LLE). In the present work various application of robotics in lower extremity orthotics were studied and trends reviewed in the advancements in controller technology. The review also analyze assistive orthotic exoskeleton systems catering to the areas of application of the hip, knee and ankle. Another finding of the study on usage application is that fuzzy and PID controllers were mostly-applied to knee areas because of their fine-tuning with area of application. Based on the review, five different categories of control methods were devised. It was found that sliding mode control (SMC) dominated as the most used controller in LLE research. The study provides an overview of the evolving trends in control methods like reinforcement learning, deep neural networks and hybrid control systems. Further the work concludes that there are very few control methods catering specifically to assisting movement of ankle joint.

Keywords: Orthotics, Lower Limb Exoskeleton, Controllers, Rehabilitation devices

INTRODUCTION

LLE is a wearable electromechanical device which enhances the physical performance of the wearer. It is a mix of technologies including bionics, robotics, information science, and control [1]. LLE should be safe, light in weight, affordable, energy efficient, have sufficient battery power, efficient command, control, good mechanical design, advanced actuators, controllers that could successfully overcome the errors [2]. LLE is indicated for assistive, locomotor, neurological, geriatric conditions [3]. The application of LLE is broadly categorized as rehabilitation, which includes training, therapy, impedance control, augmentation for stable body individuals. It enhances strength and endurance for day today

activities, fulfill occupational needs in consonance with the assigned responsibilities with reduced efforts, energy and metabolic cost [4]. LLE combines robotic strength and human intelligence and is fastened to the wearer [5]. From the perspective of control, the wearer and exoskeleton work together in a closed loop. The core components of LLE are sensors, actuators and controllers [6]. In LLE the inbuilt integrated actuators produce the requisite joint torques to act against floor reaction force and provide active forces in order to attain the lower extremity movements [7]. Sensing technologies integrated into exoskeletons provide real-time feedback on user movements, muscle activity, and pressure distribution, enabling better control and

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customization of assistance [8]. LLE are now designed with adjustable sizing, padding, and ergonomic considerations to ensure better fit and reduce discomfort during prolonged use. LLE aim to seamlessly integrate with the user's natural movements [9]. Advanced control algorithms enable adaptation to different walking speeds, terrains, a more natural, symmetrical walking pattern, stable support and balance during walking or standing; thereby optimizing the assistance provided, minimizing energy consumption and improving overall efficiency [10]. By reducing the metabolic cost of walking, LLE aim to enable users to walk longer distances with less fatigue. As the technology matures, efforts are being made to reduce the cost of exoskeleton systems [11]. Streamlined manufacturing processes, improved component durability, and economies of scale are driving down the costs, making exoskeletons more accessible to a wider range of users [12].

Rapid advancements in area of mechanical systems, electronic control, automation technology, human biology and advanced material's have led to the development of exoskeleton-like devices. Nicholas Yagn [70] conceived a device to facilitate walking, running, and jumping in 1890. His apparatus was made up of a big bow spring that was attached to a foot attachment and a hip belt. Yagn's device was entirely passive and powered by the wearer. When researchers from the US, Japan, Germany, and other European nations proposed numerous innovative concepts of man-machine systems in the late 20th century, the study of exoskeleton-type systems flourished. In 1948, Dr. A. Nicholaia Russian, biomechanist developed Power-assisted exoskeletons. Professor Bernsteinn developed prototypes for war casualties, electric-motor driven prosthesis for an above knee, to provide movement. However, exoskeleton-type system with motor actuators design was never implemented. In 1960-Hardyman (Human Augmentation Research and Development Investigation) system was designed by GE company where in the soldier could drive it through its hydraulic system to provide more strength for loading more weapons. In 1969, the kinematic walker was developed. The first active exoskeleton that provides 3 degrees of freedom per leg was developed in 1970 which was known as 'partial exoskeleton'. In 1978, self-contained, microcomputer controlled active suit/exoskeleton was developed. In 1991, a complex, human powered, kinematic 'Spring Walker' was developed as a passive exoskeleton for running. 'Hybrid Assistive Leg' (HAL) was created in 2002 by Tsukuba University in Japan. In 2004, the 'Berkeley Lower Extremity Exoskeleton' (BLEEX) powered the hip, knee, and ankle in the sagittal plane using linear hydraulic actuators. An exoskeleton featuring rotary hydraulic actuators at the hip and knee and a linear hydraulic actuator for the ankle was developed by Sarcos in 2004. An exoskeleton with lower extremities for gravity -balancing was created in 2006. Sogang University created the EXPOS tendon-driven exoskeleton device in 2006. In 2007 treadmill-based exoskeleton ALEX (active leg exoskeleton) was designed in University of Delaware. In 2010, 1-DOF exoskeleton was developed. This stationary exoskeleton assisted in knee flexion and extension exercises. During the same time a Moon Walker was also developed. In 2011 Nanyang Technological University (NTU) came up with an innovation in over ground walking rehabilitation device which they called Natural and tunable rehabilitation gait system. In 2012 a robotic orthosis powered by pneumatic artificial muscle actuators was proposed by University of Auckland, proposed. In 2012 ReWalk device having motorized hip and knee joints for both legs came in the market. In 2013, a walking assistance LLE for Paraplegic Patients named eLEGS (Exoskeleton Lower Extremity Gait System) was built by Vanderbilt University. Another design which was treadmill-based exoskeleton was developed by Jiao Tong University at Shanghai. An ankle exoskeleton was designed in 2015 that takes care of assisting humans with reduced energy costs. A soft suit for the hip joint was designed in 2016 by Harvard University on similar lines MIT designed an active autonomous ankle exoskeleton in 2016 [13].

LITERATURE REVIEW

In the present work 59 research papers were reviewed on control systems used in LLE. R. Jiménez, *et al.* [14] reviewed the used control algorithms for prosthetic/orthotic (P/O) devices and exoskeleton systems for assisting ankle motion, particularly gait support. They further provided details on algorithms pertaining to hip and the knee systems which impact the ankle. M.S.H. Bhuiyan [15] along with his team focused on classifying the control systems for prosthetics, orthotics, and exoskeletons

systems for limb rehabilitation on the basis of their functionality and working. Mainly the classification was made based on electrical, mechanical and hydraulic powered system. It lacks comprehensive review for lower limb rehabilitation exoskeletons, especially the details of the core control algorithms. Tucker *et al.* [16] proposed a general framework for the control methods used in portable gait-assistance devices, including both prosthetics and orthotics. The framework was a three-level hierarchical classification, consisting of a high, mid and low-level of control, resembling the structural and functional division of the human central nervous system. The underlying hardware aspects such as the actuators and energy storage mechanisms were also discussed in their research. The work also studied active and passive safety mechanisms and their importance in real-world for prosthetic and orthotic devices. A “modular” framework was presented by R. Baud, *et al.* [17] to classify control strategies gait assistance and is based on the three-level controller framework proposed by Tucker, *et al.* [16]. The paper abstracted the control methods from the underlying hardware and implementation and proposed a total of 31 “blocks”, which were fundamental units for division of control strategies. It also reviewed the various evaluation metrics used for exoskeleton assisted gait. A recent review by R. Huang *et al.* [18] presented the advancements in the lower limb exoskeleton space. It compared the various physiological and traditional cooperative control methods for lower limb exoskeletons. It also proposed the possible usage of virtual reality as a technique for human-machine coordination and control for future devices. Other reviews [19, 20] though exhaustive in nature, do not provide a comprehensive discussion on the control methods for such systems. In the present review, the comparative analysis with respect to the application of various control methods have been made. While preparing classification, hardware aspect is not taken into consideration. Most of the reviews done on controllers by researchers (and are available in the literature) has made three-level hierarchical classification i.e. high, mid, low-level control. In the present work a new approach has been worked out leaving aside the conventional approach [23, 25].

CONTROLLER TYPES

Controller is the brain of lower limb exoskeleton. Based on their motion and usage following types of controllers were studied as given the Figure 1.

In the present work Sliding Mode Controller (SMC), Proportional-Integral-Derivative Controllers (PID), Compliance Controller, Hybrid Controller and Other controllers were studied and analysed. Gait trajectory can be approximated and predicted using machine learning algorithms by extracting features from recorded gaits [26]. Significant efforts have been made by researchers towards the development of optimized controllers [27]. The description of the analyzed controllers is given below.

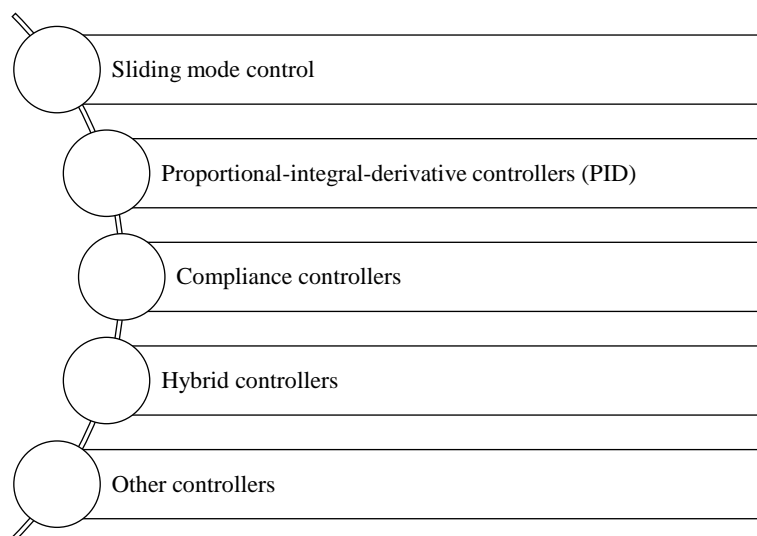


Figure 1. Controllers types.

Sliding Mode Control (SMC)

A discontinuous term that ensures system stability while addressing model uncertainty makes up SMC as a variable structure control (VSC), which is composed of a nominal component like a feedback control rule. As a result, depending on the status of the state variables, the SMC alternates between two values. As a component of the lower limb exoskeleton control system, the knee joint's flexion and extension are controlled by the sliding mode algorithm [1].

A novel two-degrees-of-freedom parallel compliant ankle rehabilitation robot that is powered by pneumatic muscles (PMs) was proposed. In order to address the nonlinear properties of the PMs and the uncertainties between the human and the robot, an adaptive back-stepping sliding mode control (ABS-SMC) technique was employed [28]. An actuated knee-joint power orthosis using control strategies based on second-order sliding mode controller was applied on a dynamic model of lower limb. Real-time experiments were conducted which showed satisfactory performance improvement in comparison to classical controllers, in terms of robustness to uncertainties and external disturbances [1]. A robust, subject-intention controlled actuated orthosis was also proposed. Electromyogram (EMG) signals were measured on the quadriceps muscle, which were given as input to a trained Radial Basis Function Neural Network (RBFNN), which then estimated the desired movement. A Second order Sliding Mode Control (SoSMC) was developed and used to control a "Shank-foot Orthosis" system. Experimental results have shown the system to be robust and stable against co-contraction test [5]. Other systems [29, 30] also used RBFNN systems for hip, knee and ankle joints. A seven-degrees-of-freedom system using dual RBF neural network adaptive sliding mode controller was also proposed to track gait profile [31]. A robust terminal sliding mode control combined with a non-linear observer on a model integrating human shank and orthosis was compared with basic SMC and SMC with non-linear observer [7]. Experiments showed that the proposed system was more robust to external disturbances and accurate with respect to position tracking [2]. An active rehabilitation exoskeleton orthosis that used a non-singular terminal sliding mode control was also proposed [6]. Experiments were conducted online on a dummy and healthy subject. Comparative performance analysis between the system and conventional controller illustrated the efficiency of the former. Some other devices also made use of terminal SMC techniques [32–34]. The use of neural networks to tune proxy-based sliding mode control (PSMC) gains online as well as their implementation for a lower-limb rehabilitation robot powered by pneumatic artificial muscle (PAM) actuators was found in [35]. Experimental analysis found that proposed system was more robust than original PSMC. A robust adaptive sliding mode controller for a human-driven knee joint orthosis was proposed [36]. Model of a shank-orthosis system was generated and its parameters were identified. Experiments were performed and the system was found to reduce time required to eliminate uncertainties and had precise position tracking. It was proposed in [37] that in lower limb exoskeleton with two degrees of freedom linear-extended-state-observer-based (LESO) robust sliding mode control reduced the effect of parametric uncertainties and unmodeled dynamics. This research ensured robustness and dynamic performance of the system and "estimated the immeasurable real-time joint angular velocity directly.

In order to simulate a 3 Degree of Freedom (DoF) robot model that supported lower extremity rehabilitation exercises for stroke patients, the sliding mode controller was used in [38]. For each joint, the model established a dynamic differential equation. Control was provided through the research model's links and sliding mode controller. Ankle, knee, and hip joint drive simulations for two cases—without and with load—were performed using Matlab software. The investigation's findings demonstrate that, when applied to the research model, the sliding controller causes only minor angular errors while maintaining a low joint torque in comparison to earlier studies. The results of this study were used to calculating and selecting parameters for the actuator when manufacturing the actual equipment. Another implementation of SMC involves the use of super twisting sliding mode controller (ST-SMC) [21, 39–44]. A super-twisting algorithm (STA) came into existence that was designed for high robustness, to preserve fast convergence with high accuracy. STA algorithm performance well under external disturbance and uncertainty. There was less chattering improved performance with this

kind of arrangement. Optimisations of SMC based on the grey wolf algorithm [42, 45] make use of the optimised parametric values from the algorithm to develop robust and fast response of the system without knowing upper bounds in advance. Observers based on SMC [46, 47] also achieve external stability by adjusting positional gain of the joint. Other adaptive sliding mode control systems make use of nonlinear control laws [48, 49] to provide robustness against disturbances. Yan et al., 2017 proposed a proportional switching function-based SMC for enhanced trajectory tracking applications [10].

Proportional Integral Derivative (PID) Controllers /Proportional Derivative (PD) Control

Proportional-integral-derivative (PID) controllers are a type of control system that are commonly used in lower limb exoskeletons to regulate the movement of the joints. PID controllers receive feedback from sensors that measure the position, velocity, and acceleration of the joints. This feedback is used to calculate the desired torque that should be applied to the joints in order to maintain the desired trajectory.

PID controllers have several advantages over other types of controllers. They are relatively simple to implement and tune, they are robust to disturbances and noise, and they can track desired trajectories accurately [24, 50, 51]. The dynamics of a nonlinear system are transformed into a linear system using PD controller by either integrating it with a feedback linearization mechanism [52] or by using it to formulate an affine PD control law [53]. A four-degree-of-freedom exoskeleton system using a fractional-order PID controller provides enhanced reference trajectory tracking in terms of stability and accuracy [54]. Using a PID control in a three-loop cascade controller provides for motion control and position tracking for hip and knee joint exoskeleton system despite external disturbances [12].

Compliance Controllers

Compliance controller uses parameterized joint trajectories as equilibrium points and allows minor forces to diverge slightly from those equilibrium points to allow for some compliance [55]. A six-degree-of-freedom exoskeleton using compliance controller was found to have a more natural gait [2, 3].

Hybrid Controllers

Hybrid controller integrates one or more type of control methods to achieve better performance than standalone controllers. Integrations with SMC include simpler controllers like fractional order fuzzy adaptive SMC with a non-linear disturbance observer [22], fuzzy adaptive SMC for reducing torques [56] or others where outer loop of control system consists of variable admittance controller and inner loop is a SMC [57]. Event driven sliding mode control methods incorporate SMC with deep differential neural networks [58], mathematical models [59] or impulsive control methods [60], which are found to be more precise and resource efficient as compared to time-tracking methods. An Active Disturbance Rejection Control (ADRC) along with SMC showed improved tracking accuracy and robustness as compared to ADRC-PD controller [61]. Fuzzy-PD or fuzzy-PID controllers [9, 51, 62] are another class of hybrid controllers with the ability to handle nonlinearity as well as enhanced sensitivity and stability to the system. A single leg exoskeleton that uses a “model-based gravity-compensator PD impedance controller” was found useful for children with cerebral palsy (CP) [63]. Systems making use of fuzzy or PID control at low level and finite state control at middle level for walking and standing-sitting motion in paraplegic patients [8] offer a customizable interface along with robustness against external disturbances. Multi-loop control system combining active disturbances rejection control (ADRC), sliding mode control (SMC) and proportional derivative (PD) control eliminate chattering phenomenon produced by a conventional SMC to produce enhanced tracking results for a 1-degree-of-freedom knee exoskeleton [64].

Other Controllers

An adaptive particle swarm optimization admittance control algorithm (APSOAC) was proposed [31] as an enhancement to the particle swarm optimization (PSO) algorithm which provides for more adaptive and flexible human gait. Series Elastic Actuator (SEA) based exoskeleton using an impedance control was found to have good stability and performance [65]. Passive-assist gait rehabilitation

exoskeleton system for pediatric applications using a robust adaptive backstepping control method [66] was found to outperform a PD-controlled system. A hierarchical controller design consisting of a discrete-event controller at the mid-level was also simulated [11]. A novel initialized model reference adaptive controller (IMRAC) for a wearable LLE exoskeleton produced robust trajectory tracking for bipedal human walking [25]. Machine learning approaches like reinforcement learning have also been used in an exoskeleton system, using deep neural network approaches [67]. The system was found to be useful for quadriplegic and hemiplegic patients via strong robustness outcomes. A compensation control method [68] is used to compensate the gravitational forces on a hip-knee exoskeleton, particularly useful for heavy LLEs. To improve balance during human-exoskeleton interaction, a “self-coordinated” velocity vector controller was devised [69] with double layers. The controller was successful in outperforming balance-guiding ability when compared to impedance control methods.

METHODOLOGY

In the present study, 59 papers were considered, consisting of 62 lower extremity exoskeleton (LLE) orthotic systems (some papers proposed multiple systems; each system was considered an atomic entry for review). An elementary exploratory analysis was performed, wherein the references were screened by title and relevance. In the second step, the selected references were filtered by their abstract and drawn conclusion. The inclusion and exclusion criteria are listed in Table 1.

After initial analytical review of the references, broad categorization of data was done and a database was prepared (Table 2). The criteria of categorization is based on the following broad parameters:

1. *Control system*: This parameter includes the controllers/control systems that the references included along with the LLEs.
2. *Type of control algorithm*: This was determined using the baseline control algorithm for development of the proposed control system. For example, “Adaptive Super Twisting Sliding Mode Control” [21] is based on the “Sliding Mode Control (SMC)” approach.
3. Proportional Integral Derivative (PID) Control/Proportional Derivative (PD) Control
4. Compliance Controllers
5. Apart from the specific control algorithms, following two categories were created.
6. *Others*: this consisted of controllers which were less than 2 in number, or controllers which pointed to a niche area of application
7. *Hybrid*: this consisted of systems combining two or more control methods, e.g. Fractional Order Adaptive Fuzzy Terminal SMC [22]
8. *Area of application*: This provided the area where the system aimed at assisting. Since it is a lower extremity system, combinations the hip, knee and ankle joints were the targeted areas of application.
9. *Degrees of Freedom (DoF)*: The degrees of freedom of the proposed orthosis (wherever the DoF was not mentioned explicitly, the DoF used in the parameter setting during simulation was used/DoF was determined based on the actuator position of the exoskeleton)

Table 1. Inclusion and exclusion criteria for the reviewed papers.

S.N.	Inclusion criteria	Exclusion criteria
1.	Systems implementing existing control method	Review papers studying advancements in orthotic devices
2.	Systems using novel methods based on extensions of control method	Upper extremity orthosis exoskeleton systems
3.	Years of Publication: 2013-2023	Lower limb orthoses that did not make use of any exoskeleton
4.	<i>Type of publications</i> : conference, article, journal, theses	Where controller method was not well-defined with experimental outcomes
		Where proposed system did not achieve significant results as to outperform existing systems
		Exoskeleton systems pertaining to applications other than rehabilitation (like powered exoskeleton for load lifting applications)

Table 2. Selected entries from the prepared database.

Year	Title	Proposed control system	Type of control algorithm	Area of application	DoF
2014	Development of a lower-limb active orthosis and a walker for gait assistance [2]	active compliance controller	Compliance	Hip, knee and ankle	6
2015	A second order sliding mode control and a neural network to drive a knee joint actuated orthosis [5]	RBFNN-SoSMC	SMC	Knee	1
2017	An intelligent control for lower limb exoskeleton for rehabilitation [23]	Adaptive fuzzy controllers used hip, knee and ankle joints	Fuzzy	Hip, knee and ankle	3
2018	Mathematical modeling and control of lower extremity exoskeleton [24]	PID	PID	Hip and knee	2
2019	Fractional order adaptive fuzzy terminal sliding mode controller design for a knee joint orthosis [22]	Fractional Order Adaptive Fuzzy Terminal SMC	Hybrid	Knee	1
2023	Optimally initialized model reference adaptive controller of wearable lower limb rehabilitation exoskeleton [25]	Initialized model reference adaptive controller (IMRAC)	Others	Hip and knee	4

DISCUSSION

Figure 2 shows the distribution of the devised control methods in the reviewed systems. The number of systems implementing Sliding Mode Control (SMC) was the highest (29), followed by Hybrid control methods (14), Other control methods (8), PID Control (7) and Fuzzy and Compliance Controllers with 2 systems implementing them each.

The distribution can be attributed to the chatter-free phenomena exhibited by SMC and the overall performance and tracking accuracy improvement by using Hybrid techniques and newly introduced other techniques like reinforcement learning [67]. A trend can also be seen by the increasing number of research conducted in the areas of these type of controllers over the years, as shown in Figure 3.

Based on the application, it can also be seen (Figure 4) that the highest amount of research has been conducted for integrated systems for the hip, knee and ankle areas (29), followed by hip and knee (19), knee (13) and the ankle (1). This trend shows that more research needs to be done in the area of supporting the movement of ankle-foot orthosis.

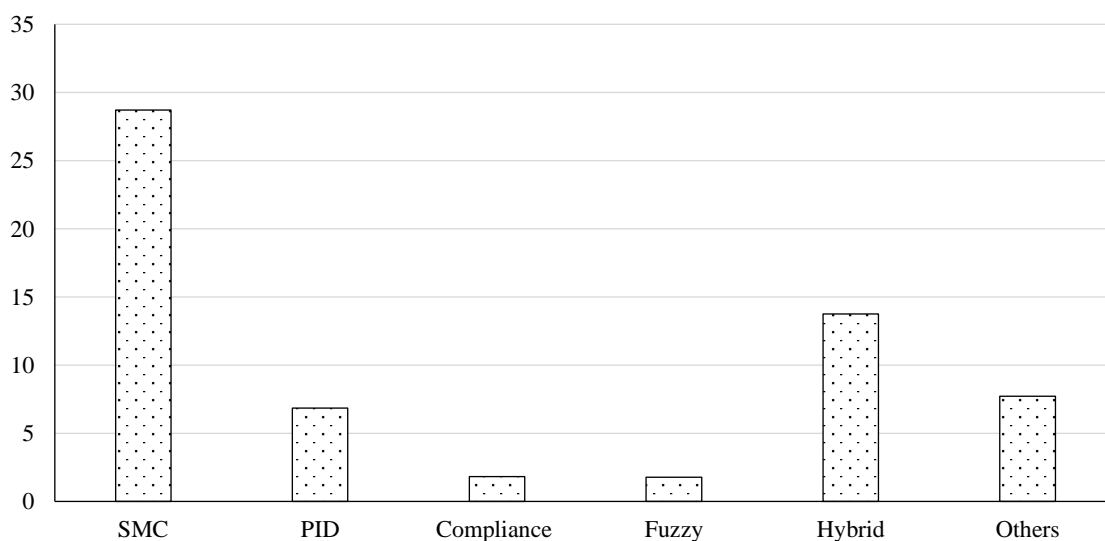


Figure 2. Distribution of control methods in reviewed systems.

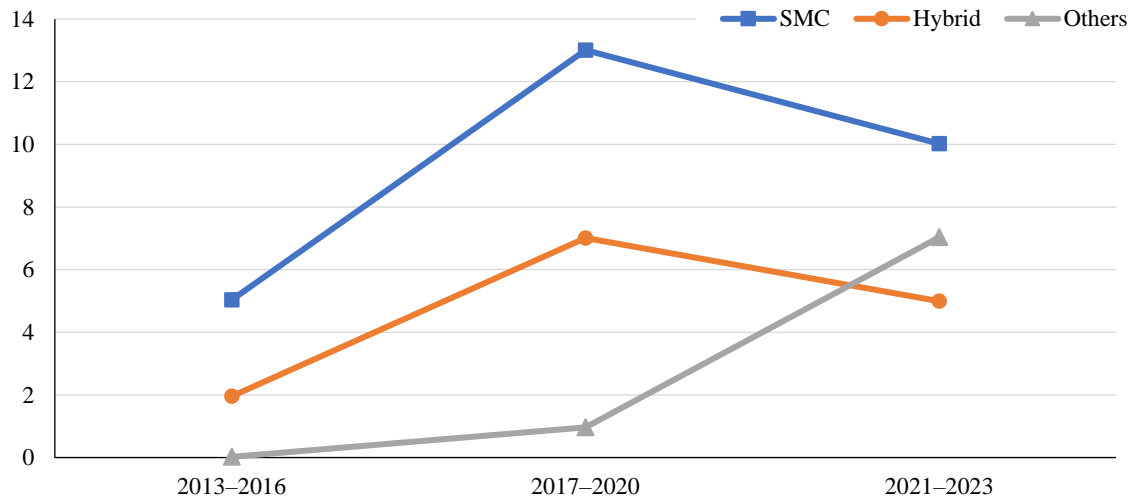


Figure 3. Distribution of research using SMC, hybrid and other controllers over the years (2013–2023).

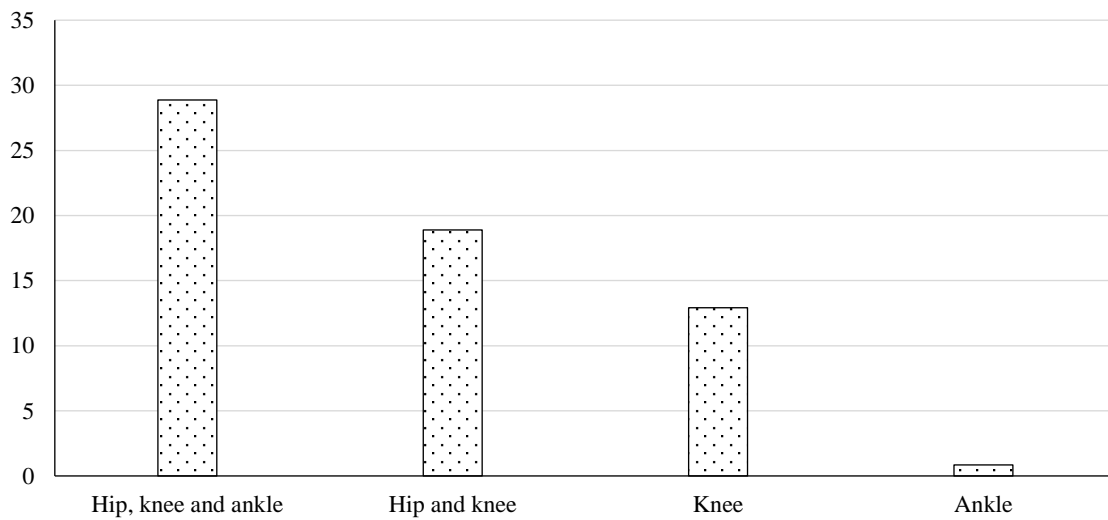


Figure 4. Distribution of area of application for the LLE system.

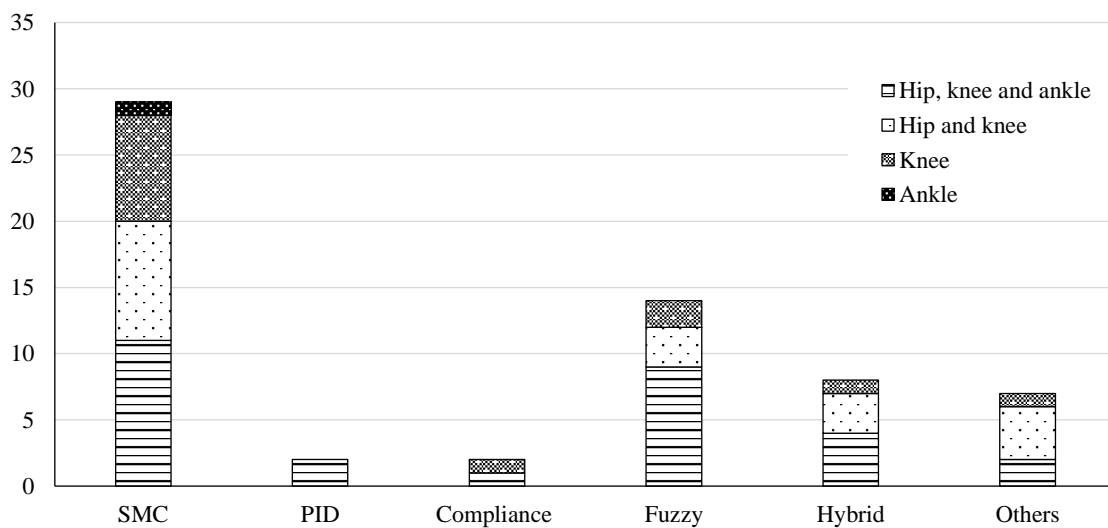


Figure 5. Distribution of area of application grouped by type of controller.

Another trend which was observed in the study was the relationship between the type of controller and the area of application (Figure 5). It can be observed that except for fuzzy and PID controller, the combined area of application of the hip, knee and ankle was the highest for every other controller, due to their high level of robustness and fast response. Fuzzy and PID controllers were mostly-applied to knee areas because of they can be easily fine-tuned for the corresponding application.

CONCLUSION

In this paper, a brief review of the various control methods used within LLE systems proposed between 2013-2023 was provided. A review of literature was also provided based on existing research and a different methodology of classification not based on the common three-level (high, mid and low level) hierarchy. Exploratory analysis was conducted of 59 different research papers proposing assistive orthotic exoskeleton systems catering to the areas of application of the hip, knee and ankle. Based on the analysis, the systems were divided into six different categories based on the control method- SMC, Hybrid, PID, Fuzzy, Compliance and Others. A statistical analysis of the research trends was also presented, implying the increasing usage of novel control methods over the years, and the need for more research in ankle-foot orthosis exoskeleton devices. The number of systems implementing Sliding Mode Control (SMC) was the highest as it exhibit chatter-free phenomena and the overall performance, followed by Hybrid control methods which attribute to overall performance and tracking accuracy. It has also been observed that the highest amount of research has been conducted for integrated systems for the hip, knee and ankle areas followed by hip and knee , knee and the ankle. More research needs to be done in the area of supporting the movement of ankle-foot orthosis. It can be observed that except for fuzzy and PID controller, the combined area of application of the hip, knee and ankle was the highest for every other controller, due to their high level of robustness and fast response. Fuzzy and PID controllers were mostly-applied to knee areas because of they can be easily fine-tuned for the corresponding application.

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