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Review Article

Balance and stability issues in lower extremity exoskeletons: A systematic review

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ABSTRACT

The lower extremity exoskeletons (LEE) are used as an assistive device for disabled people, rehabilitation for paraplegic, and power augmentation for military or industrial workers. In all the applications of LEE, the dynamic and static balance, prevention of falling, ensuring controller stability and smooth human-exoskeleton interaction are of critical importance for the safety of LEE users. Although numerous studies have been conducted on the balance and stability issues in LEEs, there is yet to be a systematic review that provides a holistic viewpoint and highlights the current research challenges. This paper reviews the advances in the inclusion of falling recognition, balance recovery and stability assurance strategies in the design and application of LEEs. The current status of research on LEEs is presented. It has been found that Zero Moment Point (ZMP), Centre of Mass (CoM) and Extrapolated Center of mass (XCoM) ideas are mostly used for balancing and prevention of falling. In addition, Lyapunov stability criteria are the dominant methods for controller stability confirmation and smooth human-exoskeleton interaction. The challenges and future trend of this domain of research are discussed. Researchers can use this review as a basis to further develop methods for ensuring the safety of LEE's users.

1. Introduction

Losing balance is a terrible incident that causes falling. This is a common phenomenon that creates a high risk for many people in domestic and professional scenarios. Information from the US Department of Labour (https://www.osha.gov/oshstats/commonstats.html) indicated that falling is the major cause of the death of workers in construction industries, which accounted for about 39.2% of total fatalities in 2017.

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Abbreviations: LEE, lower extremity exoskeletons; ZMP, Zero Moment Point; CoM, Centre of Mass; XCoM, Extrapolated Centre of mass; GRF, Ground Reaction Force; HAA, Powered hip ab/adduction; SWAA, Step-Width Adaptation Algorithm; HFE, hip flexion/extension; SM, Stability margin; GCP, Ground Contact Point; IP, Inverted pendulum; APO, Active Pelvis Orthosis; ANN, Artificial Neural Network; MLPNN, Multi-Layer Perceptron Neural Network; SMC, Sliding Mode Control; PRM, Poincare return map; CaM, Centroidal angular momentum.

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Age is another factor that raises the risk of falling. The danger of accidental death due to falling for people aged 80 and above is 90 times higher than that for people aged 60 and below [1].

Significant research efforts have been dedicated to the design and development of lower extremity exoskeletons (LEE) over the past decades [2–4]. For example, The design of hip joint assistant asymmetric fully constrained parallel mechanism prototype was presented in [5,6]. The prototype has three actuations and three rotation degrees of freedom. To avoid the disadvantages of conventional RRR-leg, pantographs were used as a three-rotation constrained leg. Genetic algorithm-based optimized adaptive ankle exoskeleton for walking assistance was proposed in [7]. The limitation of the conventional series elastic actuator (SEA) was overcome by employing a novel compact variable stiffness SEA with a nonlinear spring, which can passively change the spring stiffness as a function of output load. In recent years, the demand and usage of LEEs are gradually increasing in diverse applications. The main applications of LEE are assistance, rehabilitation and power augmentation [8,9]. Powered LEE gives additional energy to the wearer's neuromuscular system to aid rehabilitation, replace functional loses related to pathology or age, carry additional loads, and neurological retraining after injury [10]. Disabled individuals are able to live a quality life independently in societies as a result of LEE [11].

Stability is one of the most serious concerns for the current LEEs. Most of the applications for human movements such as walking, jumping, running, climbing, sit-to-stand and stand-to-sit are unstable [12]. Ensuring stability and balance for the LEE's user is a critical and difficult task. Sophisticated control strategies or supplementary external supports are often required to achieve stability. Significant studies have been conducted in the domain of falling recognition, both in terms of hypothetical modelling and sensor instrumentation [13–15]. Also, the condition for balance recovery of coupled LEE is designed using several phenomena. The present paper considers both stability and balance issues associated with LEE. It is important to distinguish between stability and balance of LEE. The stability is a general term looking into stable operation of a coupled LEE, while balance function is related to maintaining stable upright gait/posture of human-exoskeleton system. Instability does not always cause loss of balance, and loss of balance is not always caused by unstable exoskeleton's control system.

Various relationships between the Centre of Mass (CoM), Extrapolated Center of mass (XCoM), Centre of Pressure (CoP), Zero Moment Point (ZMP), Ground Reaction Force (GRF) and stability margin (SM) have been widely used in different ways to formulate the static or dynamic stability conditions of the coupled LEE and user [16–18]. The maximum Floquet multiplier, the maximum Lyapunov exponent, variability measures, long-range correlation, foot placement estimator, stabilizing and destabilizing forces, maximum allowable – perturbation and gait sensitivity norm are other measures for estimating gait stability [19]. Depending on the situation, the stability recovery can be achieved using one or combinations of the following strategies: hip strategy, ankle strategy, step strategy, squat strategy, and so on [16]. The hip and ankle strategy are dominant during stance. On the other hand, Lyapunov stability criteria are widely used to guarantee the stability of the controllers, switching technique and smooth human-exoskeleton interaction [20–22]. Other methods used by researchers to confirm the stability of coupled LEE and wearer include $H\infty$, integral admittance shaping, Tikhonov's theorem and least square logic [20,23–26]. It should be noted that static stability or static balancing refer to the stability or balancing of the coupled LEE in a static position. On the other hand, the dynamic stability or balancing means the stability or balancing of the coupled LEE in motion [27]. The human gait is defined as a dynamically balanced process, which comprises statically unbalanced phases throughout the cycle [17]. The trajectories of a coupled LEE mechanism depend on two types of stability criteria: static stability and dynamic stability. Static stability limits the vertical projection of the CoM of the coupled LEE to the inside of the support polygon. The support polygon is the area represented by the stance foot of the LEE during the single-support phase and the bounded area between the supported feet during the double-support phase [28]. Static stability leads to slow gait and LEEs with large feet. Dynamic stability delivers more freedom than the static stability since the projected CoM of the coupled LEE may leave the support polygon and thus allow for faster gait [18].

Even though dynamic stability can be accomplished using various control methods [17,29,30], slips, trips, and unexpected disturbances can still cause falling [31]. Falling is a crucial challenge in an ageing society since it is among the frequent causes of hospitalization and even death [32,33]. Apart from muscle weakness, a key factor causing falling is losing balance control ability [33]. When LEE and wearer are under an unstable state, an elderly person cannot respond and adjust motion, leading to falling [30]. In LEE, the ability to recognize falling and balance recovery is very important to confirm the security of the wearer particularly for individuals with weak balancing capability [34,35]. However, numerous exoskeletons have achieved the desired aim in providing dynamic stability. For example, BLEEX [36], XPED2 [37], Ekso (earlier eLegs) [38], Rex (Rex Bionics) and Re-Walk [39] are effective in providing assistance for a variety of motions [40].

Many reviews on different aspects of LEE have been presented. For example, the LEE for rehabilitation after stroke was discussed in [41]. The authors provided a comparison, classification, and design summary of the training paradigm, driving modes, and control strategy of the LEE in the reviewed literature. The state-of-the-art techniques for typical prototypes of LEE rehabilitation robots were analyzed and summarized in [42]. The authors evaluated the research advancements in human gait analysis and offered a logical review of the progress in the control and mechanical aspects of LEE rehabilitation robots. A review of LEE classified on the basis of applications for non-medical and medical purposes were presented in [3]. The reviewed LEE have been compared based on the significant problems such as control strategy, actuators, mechanisms, sensors, powering methods and materials. The need for safety regulation and standardization in non-medical and medical LEE was discussed. This include the international safety requirements. It has been stated in [3] that only a few LEEs realized full stabilization, without supporting sticks /crutches. The three major aspects of compliance in LEE (i.e. structure, actuation, and interface attachment components) were critically reviewed in [43]. The authors highlighted the advantages and drawbacks of the proposed solutions. They also recommended many promising research directions. A set of data sheets was created and made available. The created data sheets comprise the technical characteristics of the reviewed LEE. The common trends in recent studies of LEE were reviewed in [9]. The authors focused on sensors, actuators, energy sources, control strategies and materials. Recent issues regarding the design and development of LEE were reviewed in [44]. Despite the importance of the user's safety in LEE, to the best of the authors' knowledge, there is no review paper that focuses on the stability and balance of LEE. This paper aims to review the advances of the inclusion of static and dynamic balancing, falling recognition, falling prevention, balance recovery, and stability assurance strategies in the design and development of LEE. The present paper focuses on control strategies for balance and stability of the LEE. Although mechanical structure and actuators provides a foundation for the LEE balance and stability, however, this is not the focus of this article. The overview of the concepts used in ensuring the stability of the coupled LEE and wearer is presented. The challenges and future trends of the research area have been discussed.

The contributions of the paper are summarized as follows:

- This paper reviews the advances in the inclusion of falling recognition, balance recovery and stability assurance strategies in the design and application of LEEs.
- Open research challenges, general overview of the research area and future trend of balance and stability issues in LEE are highlighted for easy identification by researchers
- Researchers can use this review as a starting point for further development and exploration of other methods that assure the safety of the users of LEE

2. The method used for searching the papers

Only documents that are written in the English language (including journal articles, book chapters and conference proceedings) and show inclusion of stability analysis in the design and implementations of LEE in any application are included in this review. About ninety-one publications in this domain of research were reviewed. The papers reviewed were published between January 2005 to September 2019. Articles published earlier than January 2005, if any, were not found during the search. Six databases (electronic) were used for the initial search: Web of Science, Scopus, Springer Link, IEEEXplore, Science Direct and Wiley Online Library. The keywords used for the search were "Exoskeleton balance stability". Several combinations with falling recognition, balance, Lyapunov, Centre of Mass, Centre of Pressure, Zero Moment Point and stability margin were also used. This included using truncation, AND and OR for search term combinations: "Exoskeleton AND stabili* OR balanc* OR falling recognition OR Lyapunov OR Centre of Mass OR Centre of Pressure OR Zero Moment Point OR stability margin". A total of 2637 publications were found. We first screened the papers based on their titles and keywords. 396 papers passed the screening criteria. However, during the review processes, it was found that many papers mentioned "closed-loop stability" or "controller stability" or "system stability" in their abstract or keywords, but the stability issues were not considered in the papers at all. Therefore, these papers were not considered, and eventually, ninety-one relevant publications were found and reviewed.

3. Gait stability analysis using ZMP criteria

The objective of LEE control is to make the terminal of the supporting leg or swing leg (the upper body or swing foot) follow the desired trajectory. The desired trajectory can be generated by the wearer via the sensor, where the wearer plays an active role and the LEE is mainly used for power augmentation [45–47]. Alternatively, the desired trajectory can be obtained from the gait planning, where the LEE plays an active role in the coupled human-exoskeleton system and assists in locomotion for muscle disorder individuals [48,49]. The desired trajectory can also be obtained by using a motion capture system to perform a gait experiment of healthy volunteers [50]. The trajectory generated by gait planning must guarantee the stability of coupled human-exoskeleton system throughout the walking process. The ZMP scheme is employed to explain the stability confirmation of the planned gait. In addition, the ZMP can be used for motion planning and balance control [11]. It has been proven that the ZMP and CoP are identical [51]. Therefore, either one can be used for gait stability analysis.

The ZMP for leg's ground contacts can be defined as the point in the ground plane about which the total moments due to ground contacts become zero in the plane [52].

The humanoid can retain a stable walking if the computed ZMP stays within the convex hull of the all contacting points between the ground and the feet. The SM based on the ZMP stable region is defined as the smallest distance between the ZMP and the boundary of the stable region [53].

3.1. *ZMP based gait planning*

The gait planning of LEE can be obtained based on three methods, namely, ZMP criteria [54], Human Motion capture and energy consumption [55,56]. The ZMP gait planning, which is the most widely used, is categorised into two groups [16,17]. The first group is called an inverted pendulum method. This group uses some aspects of the dynamics' knowledge like the position of CoM and the sum of angular momentum. The second group needs the exact dynamics' knowledge such as CoM's position, mass and inertia of each part of LEE. This group depends on model accuracy. In this paper, the second group is used for demonstration. Firstly, the ankle and hip joints trajectories are planned. Subsequently, the other components trajectories are computed via inverse kinematics. The complete walking is categorized into four phases, namely, load response double support, first single support with supporting leg (subdivided into mid and terminal stance), pre-swing double support and second single support with other legs (subdivided into initial, mid and terminal swing). The illustration of biomechanical events in human walking is shown in Fig. 1. Both feet have contact with the ground during the double support phase. This phase begins with the forward

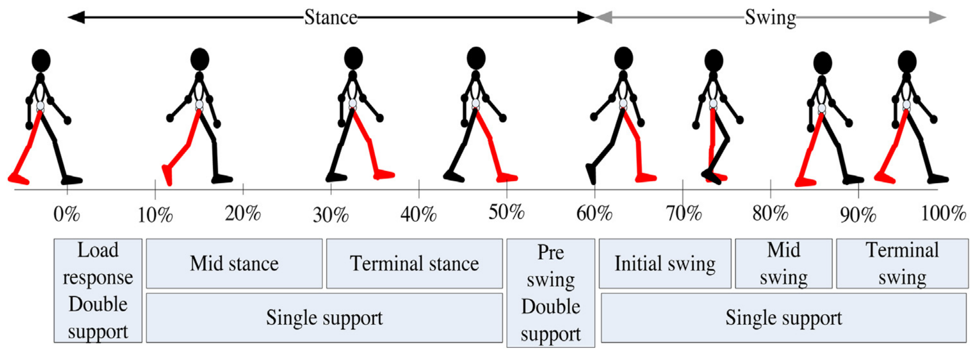

Fig. 1 – Illustration of biomechanical events in human walking (Adopted and modified from [59]).

foot heel touching the ground, and terminates with the rear toe-off. The supporting leg remains stationary while the other leg swings forward during the single support phase. Gait planning can be obtained from the first two phases since they are similar to the second two phases. Several gait planning studies assumed that the double support phases are instantaneous [57]. Nevertheless, in such a case, the hip has to move faster. This is because, to maintain the walking stability, the CoG (in the case of static stability) or ZMP (in the case of dynamic stability) must move from the rear foot to the front foot during the small period of double support. The LEE cannot walk with high speed if the period of double support is too long. The period of double support is about 20% of the complete walking period [58]. This value can be used in gait planning computations.

Wandercraft designed the full LEE called ATALANTE for paraplegic patients [30]. The wearer of ATALANTE can walk without any balance aid. Supervised machine learning and the modern optimization techniques were used to develop a smooth feedback control law that offers robust velocity regulation and disturbance rejection. The robustness and stability of the proposed method are verified through the Gazebo simulation environment. The ZMP idea was used to prevent falling off the system. It is worth mentioning that the experimental testing was done with (complete) paraplegic patients.

Currently, most stability control methods are designed to keep ZMP within the support polygon during the walking process [56,60]. These strategies are working perfectly in the humanoid robots' walking stability control. However, they may experience a serious problem in LEE because of human-exoskeleton interference. This is due to the fact that ZMP is not constantly in the support polygon in various human gait stages [45]. The human walking uses this instability for energy saving and to speed up the movement. A control method for power augmentation LEE that keeps the consistency of human ZMP and exoskeleton ZMP was proposed in [45]. The proposed control method reduced Human-exoskeleton interference while maintaining the walking stability. ZMP and CoG concepts were used to design a human-cooperative control method for LEE to help in climbing stairs in [61]. The LEE verticalization (sit-to-stand motion) problem in the sagittal plane was investigated in [62,63]. To ensure that the system remains vertically balanced, the ZMP was used to generate the desired trajectory for the generalized coordinates. The smooth and stable synthesized gait for the coupled human-exoskeleton system was obtained using the ZMP theory in [64]. A novel real-time balance control technique of LEE with ankle joints powered through variable physical stiffness actuators is proposed in [65]. An abstracted biped model, torsional spring-loaded flywheel, is used to capture approximated physical stiffness and angular momentum to achieve active balancing. The model enables the description of the mathematical relation between ZMP and physical stiffness. It is worthy to mention that the LEE used in this study was considered as a bipedal robot without any human user to clearly study the sole performance of the proposed controller.

3.2. *Practical implementation of ZMP based balancing control of LEE*

ZMP criterion can be used to generate the set point for balanced posture (i.e joint trajectories) offline. The generated setpoint is used as the desired posture to the LEE. The sensors (loadcell) are put in the strategic places in the foot, making a force plate on each foot of the LEE. These sensors are used to sense the Ground Contact Point (GCP), which determines the ZMP-like in real-time. The reference ZMP is then compared with the GCP data. The controller is designed to regulate the altered setpoints based on postures balancing identified by the loadcells. The differences between GCP and ZMP on the x–z plane can be used as the inputs to the controller. The outputs from the controller can serve as the compensated angles of the joints so that the actual ZMP can be located in the convex hull of the supporting area. Encoders can be used to sense joint locations. The simple block diagram for the practical implementation of ZMP based balancing control of LEE is illustrated in Fig. 2. The inner and outer controllers are designed for joints position control and balancing control, respectively. ZMP reference trajectory can be tracked by the outer controller based on GCP data found by the force plates in order to balance the LEE

4. CoM and CoP based balance recovery control design

It has been concluded in [66] that the CoP is a key variable that can be used by humans to maintain balance during gait. The CoP is controlled by foot placement in the mediolateral

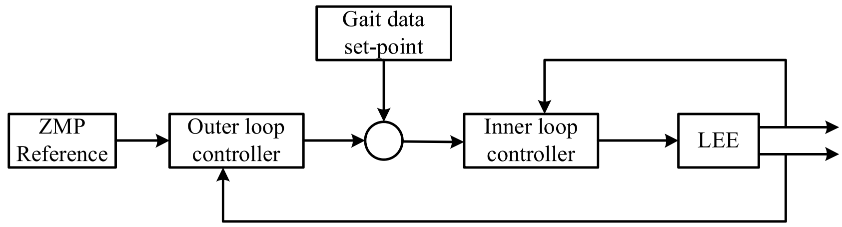

Fig. 2 – Block diagram for the practical implementation of ZMP based balancing control of LEE.

direction, and ankle torque and foot placement are used in the anterior posterior (AP) direction. If the ankle torque cannot be utilized in changing the CoP in the AP direction, humans use the foot placement adjustment method in the sagittal plane. The CoP at the end of the double support phase is linearly related to the CoM velocity at the end of the preceding swing phase [66]. The CoP corresponds to the ground projection of CoM for static posture in sagittal plane point of view and lies a bit frontward to the ankle joint during quiet standing. Another important variable for balance control is the timing of foot placement, but it is more difficult to predict. When the pilot loses balance, the CoM of the coupled system lies behind the CoM of the pilot. The CoP moves towards the heel (i.e. away from the centre of the foot), thus reducing the SM. The pilot has to recompose his stance to compensate for the negative effect. Hip strategy or ankle strategy, or their combination is used by human beings to adapt to the change in the horizontal position of the CoM in the sagittal plane [18]. It is well known that researchers are using an inverted pendulum (IP) to analyse and validate these postural balances. This is based on the analytical relation between CoM and CoP and the horizontal acceleration of CoM. In hip strategy, the CoM is shifted by moving the body as double segment IP with opposite rotation at the hip and ankle. In ankle strategy, the CoM is shifted by moving the whole body just like IP. Both the hip and ankle strategies are used at the same time in the combined hip-ankle strategy. Irrespective of the type of strategy employed to shift the CoM, it can be regarded as posture or gait distortion [27]. Different from disturbance recovery, the distortion is sustained in the case of backpack loading due to persistent loading. This kind of distortion may not be easily rectified. The additional support area needs to be provided to accommodate the CoP as illustrated in Fig. 3. The additional area can help in increasing gait stability, which is very important especially in assistance and rehabilitation applications [11]. One of the pioneer LEE research that is aimed at supporting the function of maintaining postural balance directly through the LEE is the

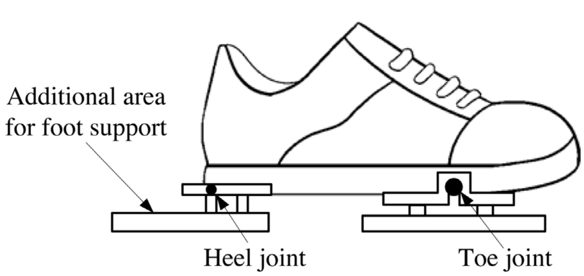

Fig. 3 – Adaptive foot device with additional support area.

"EU FP7 project BALANCE" [67]. They tried to make the LEE cooperate with its user in a natural way. This study focuses on the methods used by humans for postural control and the application of similar methods in the control of the proposed LEE, assuming that this would correspondingly support implementation of human-exoskeleton cooperative control. The methods to track the CoP and total body CoM of the person wearing the exoskeleton in real time was developed to describe the postural balance situation. A new ecological method relying on Active Pelvis Orthosis (APO) for enabling balance recovery after unanticipated slippages was reported in [68]. Precisely, if the APO senses the signs of unbalanced situations, it provides countering torques at the hips to help regain balance. This is done based on the evaluation of CoM stability and SM. Two transfemoral amputees and eight elderly persons were involved in an experimental test. The result indicated the improvement in the stability against falling as a result of the assist-when-needed behaviour of the APO. A new adaptive foot system (add-on device) to improve the stability of LEE was reported in [11]. The support area behind the heel is automatically extended during walking. The support areas of the system can increase during stance and collisions with the level ground during the swing can be avoided. This is based on the fact that the system passively extends during stance and retracts during the toe rocker phase. The proposed system does not require actuation power. The whole concept is based on the relationship between CoM and CoP. An experimental investigation was conducted on balance recovery control with a LEE in [69]. Four subjects were exposed to a perturbation during standing. The LEE produced the forward force impulse to their pelvis, forcing them to step forward with the right leg for balance recovery. The stepping duration in balance recovery was calculated using the CoP. A human-inspired balancing assistance control for LEE that enables volitional stiffness regulation is presented in [70]. A human balancing experiment was carried out to study the relationships between the anteroposterior excursions of the CoP with kinetic, kinematic, electromyographic measurements and the model stiffness of the knee joint.

The LEE that assists the paraplegic individual to regain their locomotion ability called CUHK-EXO was introduced in [71]. The reference joints trajectories were generated offline based on motion capture data considering leg geometry constraints. The CoP position is adjusted in real-time to ensure coupled system balance. The same balance control was used in [72]. The only difference is in the application and main controller type. The theoretical hypothesis of the stable gait of assistive LEE was presented in [73,74]. This is based on the synchronization of the CoM and the movement of the foot (stable quasi-static walking condition). It has been mentioned that the proposed system can assist in stable walking without the use of crutches. However, their work is based on a piecewise linear motion trajectory of the CoM.

A lower-limb paraplegics-rehabilitation exoskeleton called Hyundai Medical Exoskeleton (H-MEX) was introduced in [75]. The authors designed a trajectory for generating propulsion in the double stance phase of bipedal walking. Using the angular momentum, a successful and stable step of the leading leg foot was found. The pelvic actuators and powered ankle mechanism were incorporated in the system to provide active lateral weight shift and maintain the lateral stability. This is because the lateral displacement of CoM toward the stance leg precedes the initiation of a step [76]. Also, adapting step width is critical for lateral stability. It has been demonstrated that actively assisting lateral motion improves gait stability and eliminates the need for crutches and walkers. Therefore, it enables paraplegic patients to walk with the exoskeleton while having free hands for other usages. Five healthy subjects on the treadmill were used to evaluate the proposed control method. The torso motion was added to advance the total CoM in the stance phase forward. The fixed set value of the torso tilting angle was increased by a sinusoidal profile. Rajasekaran et al. [17] presented an adaptive control method for rehabilitation of LEE that guarantees the static stability and balance of wearer. The proposed control method has the ability to provide the required support for postural stability and balance recovery within the set stability limit based on the assist-as-needed paradigm. The concepts of CoM and CoP were used in developing the control method. In a similar manner, the static stability PARGO LEE was improved within the set limit of CoG [77].

The balance stability techniques applied to the LEE called Mina v2 were reported in [78]. The proposed balance stability strategy is based on CoM and joint-space dynamics. The balance stability analysis is based on the established equivalent mechanical model of the combined human-exoskeleton system in the sagittal plane. The flat ground stability performance of Mina v2 was analysed using stability boundaries in a double and single leg. The LEE called ATLAS that can assist paralysed children to have stable ambulation for walking, sitting and standing was introduced in [79]. This device includes the active orthosis and a stability aid device called walker. The walker has two DoFs that allow sit-to-stand and stand-to-sit comfortably in a stable way without the movement of the walker itself. The active orthosis provides stability in the sagittal plane during walking while a walker provides stability in the lateral plane. The control of the proposed system is based on the GRF and CoP. Gordon et al. [80] investigated a metric that can be optimised, allowing assistance to be applied without compromising the stability of gait and energy efficiency. A unique setup was used for collecting the experimental data, including kinetic, kinematic, torque and angular data. Based on the collected data, the metrics were compared in three walking scenarios: walking with an exoskeleton in transparent mode, walking with an exoskeleton in assistive mode and walking without an exoskeleton. The following walking contexts were studied for each of these scenarios: slow walking, fast walking, walking down an inclined plane, walking up an inclined plane and walking at baseline speed. The spatial and temporal parameters CoM, CoP, kinematics and kinetics were used for the analysis. These metrics were then compared to find the metrics which indicated the maximum invariance suitable for optimising in an exoskeleton control paradigm. The algorithm for balance control of LEE based on the inclination angle of the body's CoM relative to the CoP and the rate of change of inclination angle was proposed in [81]. The mechanical energy needed for the movement was computed using the motion of the CoM. The genetic algorithm was used to optimise the generation of joint angles reference trajectories based on CoM for STS transition in [82]. The CoP was included in the control loop in [83] to improve the balance of walking.

The disturbance in balance can be detected in the sagittal or lateral plane with respect to the stance foot, based on the estimated positions of CoM as illustrated in Fig. 4.

5. XCoM, HAA and step-width adaptation algorithm-based balance recovery control design

Powered hip ab/adduction (HAA) can also be used for self-balance walking. This is based on an online step-width adaptation algorithm (SWAA). The SWAA is based on the concept of XCoM. The XCoM concept for improving gait stability has been effectively used in various studies [27,84,85]. The stability condition can be formulated using XCoM for both dynamic and static conditions. The eminent condition for static stability in standing position is that the vertical projection of the CoM should be within the supporting area. This is based on the IP model. On the other hand, the condition for dynamic stability is that the position of the vertical projection of the CoM plus its velocity times a factor, $\sqrt{l/g}$, should be within the supporting area [86]. This vector quantity is known as XCoM. The good feature of XCoM is that it amalgamates the information about the present CoM's kinematics data to forecast a time ahead at which the CoM will contact the support boundary. In the XCoM idea, the single stance phase of a two-footed gait can be modelled as an IP.

The strategy for stability assurance in MINDWLKER exoskeleton was described in [87]. A control technique that gives gait assistance in both sagittal and lateral planes was presented. The lateral stability was improved by controlling the exoskeleton's HAA during stepping. This was realized by varying the value of HAA to alter the width of the step at heel strike. It has been reported that a healthy subject can make a pre-defined gait pattern in the exoskeleton without any balance aids. Another control and stability method for MINDWALKER exoskeleton was described in [27]. CoM was used for state transitions and a new SWAA was employed for lateral balance and stability. Both paraplegic and healthy subjects were used in testing the proposed methods. A stable walking with no balance aid has been achieved for healthy subjects. The hip exoskeleton for balance and walking assistance is proposed in [18]. This device includes powered hip flexion/extension (HFE) and HAA joints for supporting the walking and stability. The XCoM concept was used to develop the online balance controller for maintaining the gait stability of the coupled human–exoskeleton system. The proposed device

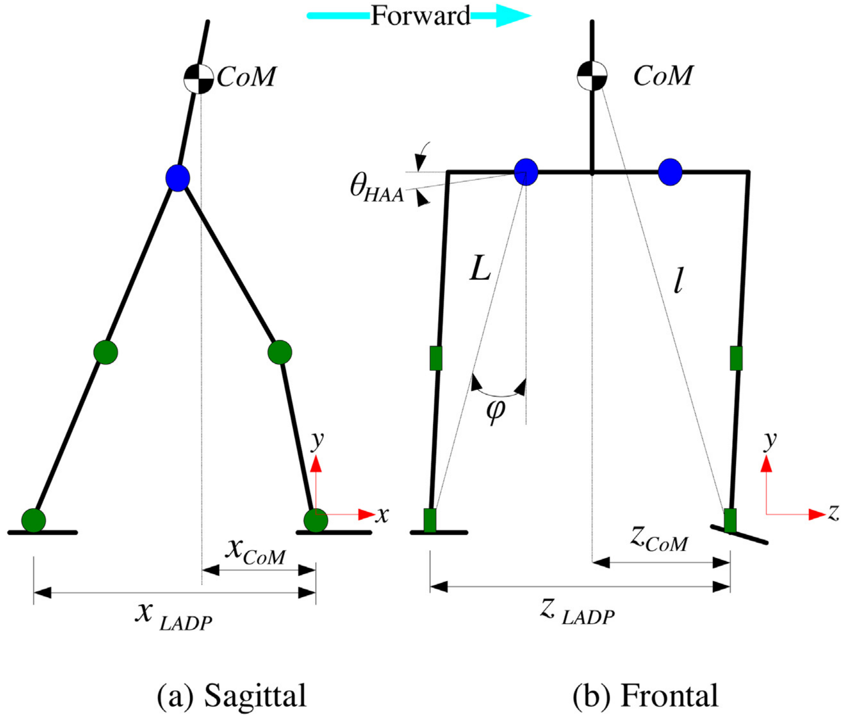

Fig. 4 – Illustration of the evaluation of the position of CoM in the sagittal and frontal planes.

used adaptive admittance control strategy to apply for support as requested by exerting a compliant control force on the leg that needs assistance during balance control.

6. Lyapunov stability method

The main aim of stability concept is to conclude the decision regarding the behaviour of a given system without a rigorous calculation of its trajectories solution. Lyapunov functions are employed to study the stability of the system's equilibrium points. Lyapunov criteria for assuring stability is the main technique used for confirming the stability of controller, switching, and human-exoskeleton interaction. Some researchers developed their controllers based on the Lyapunov theory. These are discussed in this section. In Lyapunov theory, there are two main directions: using Lyapunov function or reformulating the definitions of stability in the sense of Lyapunov and then proving the stability using a similar methodology for linear/nonlinear control [88].

The trajectory tracking tasks and human-exoskeleton interaction in the presence of additional disturbances for LEE were studied in [22]. This is based on two control methods. The first consists of the pure Artificial Neural Network (ANN) and combined error factor to improve the wearer safety by the enhanced transient response. The second includes repetitive learning control and ANN. Stabilities of the proposed controllers are thoroughly verified in a Lyapunov way which is the same as in [89]. The bounded control method of a knee-joint LEE that ensures knee flexion/extension movements during the rehabilitation and assistance processes was proposed in [90]. The Lyapunov theory was used to prove the following: 1) the trajectories ultimate boundedness in the presence of parameter uncertainties; 2) the asymptotic stability of the shank-foot-exoskeleton in the absence of a human active effort, and 3) the input-to-state stability with respect to a bounded human active torque. The performance of passive/resistive rehabilitation and assistance-as-needed was tested experimentally. A constrained control torque is applied to ensure the asymptotic stability of the shank–foot–orthosis in [91]. A tele impedance-based assistive control structure, its steady-state and transient stability analysis for a knee exoskeleton system were reported in [92]. Quadratic stability theory based on Lyapunov criteria and linear matrix inequality for continuous-time systems with polytopic uncertainties were used to guarantee stability. The stability analysis is limited within the usable range of the active stiffness. Sit-to-stand and stand-to-sit experiments were conducted with healthy subjects.

A non-singular adaptive fractional-order fast terminal sliding mode control for LEE subjected to disturbances and uncertainties was presented by [93]. The closed-loop system was confirmed to be asymptotically stable using Lyapunov proposition. Similar work (in terms of stability assurance and control methods) was presented in [94,95]. The adaptive observer-based on hybrid SMC and Multi-Layer Perceptron Neural Network (MLPNN) for knee exoskeleton is presented in [96]. The MLPNN was used to approximate the unknown dynamic. MLPNN based controller was also proposed for knee exoskeleton in [97]. The closed-loop stability was proved using Lyapunov's approach for both [96,97]. A neuroprosthesis controller that includes a modified PD-based and a variable structure controller was developed for assistive LEE [98]. In this work, the control laws do not share a common Lyapunov

Table 1 – Summary of the studies that used Lyapunov criteria for stability confirmation.

Reference	Application	Type of LEE	Type of testing	No. of Subjects
[22]	Rehabilitation	Not stated	Simulation	Not applicable
[89]	assistive	Full LEE	Experiment	Not stated
[90]	Assistive and rehabilitation	Knee	Experiment	One healthy subject
[91]	Rehabilitation	Knee	Experiment	One healthy subject
[92]	assistive	Knee	Experiment	Not stated
[93]	Not stated	Hip-knee	Simulation	Not applicable
[94]	Not stated	Full LEE	Simulation	Not applicable
[95]	Not stated	Hip-knee	Simulation	Not applicable
[96]	Rehabilitation and assistive	Knee	simulation and in experimentation with healthy subjects	Not stated
[97]	Assistive	Knee	Experiment with healthy subjects	Five subjects
[98]	Not stated	Full LEE	Simulation	Not applicable
[99]	Assistive	Full LEE	Experiment with healthy subjects	Two subjects
[100]	Assistive	Full LEE	Experiment with healthy subjects	One subjects
[101]	Assistive	Full LEE	Experiment with healthy subjects	Not stated
[102]	Rehabilitation	Knee	Experiment with healthy subjects	One subjects
[103]	Not stated	Hip-knee	Simulation	Not applicable
[104]	Not stated	Full LEE	Simulation	Not applicable
[105]	Rehabilitation and assistive	Knee-ankle	Simulation	Not applicable
[106]	Not stated	Knee	Simulation	Not applicable
[107]	Not stated	Ankle-shank	Simulation	Not applicable
[108]	Assistive	Ankle	Experiment with healthy subjects	Ten subjects
[109]	Assistive	Full LEE	Simulation	Not applicable
[110]	Assistive	Knee	simulation and in experimentation with healthy subjects	Six healthy subjects
[21]	Assistive	Knee	Experiments	Five healthy subjects
[111]	Assistive	Knee	Experiments	Five healthy subjects
[112]	Assistive	Hip-knee	Simulations and experiment	One healthy subject
[113]	Rehabilitation	Knee-ankle-foot	Experiments	Not stated
[20]	Rehabilitation	Hip-knee	Simulation	Not applicable
[114]	Assistive	Full LEE	Simulations and experiment	Five healthy subjects
[115]	Rehabilitation	Knee-ankle	Simulations and experiment	One healthy subject
[116]	Rehabilitation	Full LEE	Experiment	One healthy subject
[117]	Rehabilitation	Full LEE	Experiment	One healthy subject
[118]	Not stated	Full LEE	Experiment	Not stated
[119]	Rehabilitation and assistive	Knee	Experiment	Three healthy subjects
[120]	Rehabilitation	Knee	Experiment	Not stated

function since the error states are defined in a different way and distinct terms that compensate for electromechanical delay are employed to control functional electrical stimulation. Hence, the stability proof is complex and a Lyapunov analysis that considers a hybrid dynamical system was used. The stability analysis and the controller concept were similar to that reported in [99,100]. The main differences were in the controller and testing methods.

An adaptive ANN controller for LEE was presented in [101]. The stability studies conducted indicate that the closed-loop system is globally uniformly ultimately bounded with the state feedback controller. Similarly, the Lyapunov style was used to evaluate the adaptation laws of the ANN parameters and the inertia term in [102]. These derived adaptation laws guarantee the stability of the complete system, including wearer. The concept is the same as that in [103,104]. A constrained control method was proposed for LEE in [105]. The convergence analysis of the high gain observer and the asymptotic stability of the bounded control law without human contribution was confirmed using Lyapunov-based analysis. A combined robust adaptive admittance-based control strategy that includes admittance control, model reference adaptive control and a general function estimation technique was proposed in [106]. The tracking performance and the stability of the proposed controller were assessed in the existence of both nonparametric and parametric uncertainties using Lyapunov theorem. A summary of studies that used Lyapunov theory for stability analysis is provided in Table 1.

A direct Lyapunov-based hierarchical adaptive control scheme in cascade topology for a LEE with control saturation was proposed in [107]. The proposed method consists of a Lyapunov-based back-stepping regulator and Lyapunov-based ANN adaptive controller. The human-exoskeleton interaction torque was minimised by the proposed method. Antonellis et al. [108] studied the interaction properties of exoskeleton power and timing on gait variability. The maximum Floquet multiplier and largest Lyapunov exponent were used to evaluate the stride-to-stride variations of the kinematic time series. A command filter backstepping adaptive Fuzzy-SMC method for assisting LEE was reported in [109]. The stability of the closed-loop system was verified using Lyapunov theory. An assistive LEE trajectory control was proposed in [110]. The proposed controller consists of a nonlinear disturbance observer hybridised with a backstepping sliding control.

The optimal control law was found using GA. The closed-loop system was proved to be asymptotically stable using Lyapunov theory.

A sliding mode observer-based control method for flexion/extension of the knee joint exoskeleton was synthesized in [21] 2019. The human-machine stability has been proven mathematically using Lyapunov criteria. Five voluntary subjects, in a sitting position, were used for experimental validation. A similar stability analysis, but with a different controller, was done in [111]. The improvement of human-exoskeleton interactions suppleness and multi-joint independence in walking assistive exoskeleton based on biological control theory was proposed in [112]. An innovative human-robot interaction-based control algorithm consisting of knee joint hierarchical impedance control, hip joint central pattern generator control, and hip-knee joint linkage control was investigated. The method considers mutual inner-inhibition, which is suitable for keeping left-right hip joints antiphase relationship in order to have stable walking assistance. The proposed control stability was studied and confirmed using Lyapunov stability theory. Additionally, it has been shown that the system has an attractive domain and is stable closer to the equilibrium point. The authors also proved the control system's stability by generating the knee limit cycles. The closed-loop stability was confirmed in a similar way to [113]. A nonlinear robust adaptive sliding mode admittance controller was proposed for LEE in [20]. The stability of human-robot interaction in the presence of parametric and non-parametric uncertainties is assured using Lyapunov theorem and Barbalat's lemma. Smart assist-as-needed control for LEE was introduced in [114]. The safety implementation of the proposed control method in the experiments was guaranteed by full stability analysis. The stability of the closed-loop system was proved with and without parameter uncertainty using the Lyapunov method. The assist-as-needed problem for rehabilitation LEE was addressed in [115]. The presented controller confirms the stability of the system with bounded control command. This was achieved using Lyapunov theory. The controller proposed in [116] does not need a muscle model and is able to yield asymptotic stability for an exoskeleton model and a nonlinear muscle model in the presence of bounded nonlinear disturbances. A similar study was presented in [117]. The only difference is in the controller and the type of exoskeleton. Two parallel control methods for exoskeleton trajectory tracking were reported in [118]. The controllers can deal with human-exoskeleton interaction and disturbances. The stability of the proposed controllers was given scrupulously in a Lyapunov way. A similar stability study was proposed in [119,120]. Their main difference is in the type of controller and methods of testing.

7. Other methods for confirming the human-exoskeleton couple stability

An output feedback assistive control for LEE called FUM-KneeExo was proposed in [121]. $H\infty$ analysis was used to define the coupled stability and performance of the proposed method. Similarly, the robust $H\infty$ control technique was used in [23] to satisfy the condition of close-loop stability and robust performance. The control algorithm presented in [24,122] can produce the desired shape for the frequency response value of the integral admittance of the coupled system. Concurrently, it engenders an optimal feedback controller which can achieve the desired response and assure coupled stability and passivity. A study was conducted in [123] to investigate whether a passive unilateral LEE has an impact on dynamic and static reactive balance control. Eleven healthy subjects were used in three different balance tasks: single-leg standing, bipedal standing, and platform perturbations in single-leg standing. This investigation revealed that the exoskeleton helps under static conditions for some time. Also, the exoskeleton tended to weaken dynamic reactive balance, possibly by obstructing adequate compensatory alterations.

Hybrid automata and modified Poincare return map (PRM) were employed to address the locomotion stability issue in [59]. It has been stated that the modified PRM is more suitable for both non-periodic and dynamic walking compared with CoM and ZMP methods. The exoskeleton locomotion is controlled by a new high-level strengthening learning method called active PI^2 CMA-ES. The active PI^2 CMA-ES proved that the motion of the exoskeleton is asymptotically stable according to the modified PRM criterion. A hybrid sliding mode and iterative learning switching controller for functional electrical stimulation and the powered exoskeleton were proposed in [124]. The stability of the proposed controller was confirmed using the Lyapunov method. The overall stability, including the ground impact phase, was revealed mathematically using Poincare maps. A multi-modal control method for rehabilitation LEE was presented in [25]. This scheme consists of the safety-stop mode, which stops the LEE whenever the interaction force is too large (which may result in injuries). The proposed method guarantees the safety of the wearer by using the force feedback and regional position. The stability of the overall system was proved by using Tikhonov's theorem. A summary of studies that used other methods for stability analysis is provided in Table 2.

8. Open research challenges and future directions

The design of early LEEs has many limitations such as heavy actuators and frames, lack of measurement and control method to sense the intention of the wearer and actuate accordingly, and energy sources with a small weight to power ratios [9]. Substantial progress has been made in solving the aforementioned problems by coming up with new actuator technology [125], intelligent control methods, lightweight materials for frames and actuators, and power sources with enhanced energy density [44,126]. A complete passive LEE was also proposed to augment mobility during stance and walking [127,128]. The passive LEE does not have limited usability due to power demands, and it has lightweight since there is no need for battery packs and motors, which are often heavy and cumbersome.

Achieving and keeping balance are crucial conditions for exoskeleton-assisted locomotion. The entire modes of locomotion such as walking, jumping, climbing, running, sit-to-stand and stand-to-sit are difficult to statically keep stable [12].

Table 2 – Summary of the studies that used other stability criteria for stability confirmation.

Reference	Stability method	Application	Type of LEE	Type of testing	No. of Subjects
[121]	$H\infty$	assistive	Knee	Simulation and Experiment	Not stated
[23]	$H\infty$	assistive	Knee-ankle	Simulation and Experiment	Not stated
[24]	Integral Admittance Shaping	Assistive	Hip	Experiment	One healthy subject
[122]	Integral Admittance Shaping	Assistive	Hip	Experiment	Three healthy subjects
[59]	Poincare return map	Power augmentation	Full LEE	Experiment	Not stated
[123]	time to stabilization and CoP	Balance support	Single Leg full LEE	Experiment	Eleven healthy subjects
[124]	Poincare maps	Not stated	Hip	Simulation	Not applicable
[25]	Tikhonov's theorem	Rehabilitation	Knee-ankle	Simulation and Experiment	Three healthy subjects

Even though dynamic stability has been achieved in various pieces of literature using different control methods [12,17,59], slips, trips, and unanticipated disturbances can cause falling. Patients with neuromuscular disorders or leg injuries are in need of balance assistance aid/device for their rehabilitation period. Also, people wearing full LEE for any application are greatly in need of the assurance of balance for their safety. This is more important for assistive and rehabilitation applications.

8.1. *Human-exoskeleton interaction*

The most important features of the exoskeleton are to be comfortably worn by humans and also to work collaboratively with humans. Human-exoskeleton interaction control is very significant for two basic modes of operation: assistive force control mode and human-in-charge mode. The exoskeleton should be able to produce accurate torque/force to human limbs as required in the assistive force control mode. The exoskeleton should be able to follow the human locomotion with very little interaction force in the human-in-charge mode. It is very vital to assure the safety/stability of the human– exoskeleton interaction in both control modes. [113]. Some researchers used the Lyapunov criteria to formulate the conditions for ensuring Human-Exoskeleton interaction stability [21,111,124].

The design concept of full LEE is based on biomechanical theory and ergonomics. The design of LEE, which is an anthropomorphic device, is realised by setting the range of movement of each joint similar to that of humans. It is impossible for the wearer to sense no restraints during locomotion, such as in power augmentation, assistive or even a more dangerous task like rehabilitation. Therefore, the wearer's locomotion stability may be destroyed by the exoskeleton [59].

An adaptive control device based on the iterative learning model to track the single leg walk for LEE control was studied in [129]. The effect of the human–exoskeleton interaction torque on the tracking error was also examined. The results found indicated that the interaction torque has an unavoidable effect on the tracking error which was drastically reduced by the proposed method. The authors stated that the proposed strategy can be applied for LEE and help in the feasibility and safety of LEE for practical application. The safety and performance of LEE are greatly affected by the gait tracking accuracy. As the coupling of human-robot systems are typically nonlinear and produce unexpected errors, a traditional iterative controller may not be suitable for safe operation [129]. As such, an adaptive control method based on the iterative learning model to track the gait for LEE should be studied in practical application. Moreover, control methods that do not require dynamical or biomechanical models should be tested in LEE, just like the method proposed in [130]. The effect of mass on stability should also be discussed.

The rigorous management of human locomotive stability is the most difficult issue in exoskeleton- or orthotic-assisted locomotion. It is significantly more problematic in LEE for paraplegics. Even if the paraplegics can control their torso, the locomotive stability can only be achieved in a restricted manner since: 1. there is no enough information about the kinematics in a system with the wearer of LEE, and 2. there is a dispute between the intention of the wearer and the control method of the LEE. Also, human body variations cannot be ignored. Thus, it is strenuous to develop an assertive model-based controller.

8.2. *Stability conditions and balance recovery of the LEE*

Several relationships between the ZMP, CoM, CoP, XCoM, HAA, SWAA and SM are used in different manners to formulate the static or dynamic stability conditions of the LEE. However, most of the control methods that are formulated using these concepts focus on recovering from very small disturbance [35]. Contrary to the biped robot, the fundamental ability of LEE is to be worn by the user securely and to work collaboratively with him/her.

The ZMP scheme is used for developing a stable motion planning and balance control [11]. The ZMP method has some disadvantages: The coupled human-exoskeleton's stance foot should always remain in full contact with the ground and the planned gait may result in unnatural motion with high energy consumption [28].

Numerous tactics have been developed for falling recognition and balance recovery in the literature [11,12,17, 34,35,59]. Powered HAA is used for self-balance walking based on an online SWAA, which is based on the idea of XCoM. The XCoM concept for improving gait stability has been effectively used in various studies [27,84,85]. The stability condition is formulated using XCoM for both dynamic and static conditions.

Different Lyapunov functions have been used for designing adaptive and robust controllers in this domain of research [20–

22,93,104,107,112,114,124]. Many studies employed the Lyapunov method to prove the proposed controller stability [22,89,90]. Lyapunov-based controller is proposed using backstepping regulator [107,109,110]. It is well known that the backstepping is a Lyapunov-based design technique, which can be applied directly to strict-feedback nonlinear systems [89].

Balance control methods are designed using the relationship of the CoM and/or CoP of the human body [1]. Though it is not easy to estimate the coupled system's CoM, which includes a wearer and LEE robot [75], the CoM is a significant control element used for balance management [75,78]. Hence, instead of focusing on model-based controls, the general dynamic trend should be examined and reflected upon when designing control algorithms in order to get stable gait. An alternative method used for stability is the Poincare map [131], which is used to solve the problem of a system with impulse effects. The continuous system stability is closely associated with the corresponding point of the Poincare map stability. However, naturally, humans are unable to exactly repeat the same locomotion for a given period. Thus, the Poincare map cannot be applied to the LEE locomotion [124]. It has been demonstrated in [124] that the modified Poincare return map is more suitable for both non-periodic and dynamic walking.

The biomechanics behavior of pilot wearing an exoskeleton for unexpected perturbations should be studied in the proposed LEEs with balance recovery capabilities. Moreover, the normative data describing the kinematics of the compensatory step used to recover loss of balance while the pilot wear the exoskeleton should also be examined. These data can support further research on the potential use of LEEs to assist in prevention of incipient falls [132].

At this moment, it is difficult to declare one of the reviewed balancing techniques as the best method. This is because most of the reviewed techniques have been successfully applied and tested in real-life experiment. Centroidal angular momentum (CaM) is a potential tool for balance recovery caused by push or other disturbance. The concept of CaM is based on the coupling between the linear angular momentum and rate of change of angular momentum, and the CoM speed [28]. The CaM criterion generalizes the applied concepts like ZMP, CoM and CoP and extends their applicability [13]. The CaM has been applied effectively in balance maintenance for biped robots [13,133]. It is expected that the CaM will be used in the exoskeleton research area considering its stated advantages. The Centroidal Momentum (CM) in human walking was studied to see whether it could be used as a kind of stability index to detect the perturbations and an initial loss of balance [134]. Only the preliminary results of CM Analysis in this regard was presented. There is a need to conduct research on designing a Stability Index to assess balance of a coupled LEE using CM. Another balance maintenance criterion that is yet to be applied in this domain of research is footstep-based criteria. It is one of the efficacious approaches for recovering from push [28].

Designing an LEE consisting of the stable controller, fall recognition scheme, balance recovery strategy, balance aid free, and smooth human-exoskeleton interaction is still an open research topic.

9. Conclusions

The dynamic/static stability, balance recovery, fall prevention, proving controller stability and smooth human-exoskeleton interaction are of critical importance in the design and development of LEE. However, the majority of the reported studies in this domain did not pay much attention to these important issues. The area of stability analysis of the exoskeleton locomotion, which was given little attention, should be addressed in any kind of exoskeleton application. Safety should be the first concern in any given design. Safety is the key concern of the regulatory organizations when giving approval for the commercialization of new products. Thus, few LEEs fulfilled the international safety requirements. Users always need to have confidence in the proposed LEE for easy acceptance. The developments of the inclusion of static/dynamic stability, falling recognition, balance recovery and stability assurance method in LEE were reviewed in this paper. It has been found that the ZMP, CoM and XCoM concepts were mostly used for balancing and prevention of falling. However, despite the applicability of the centroidal angular momentum and footstep-based criteria in this area of research, they are yet to be applied. It has also been found that the Lyapunov stability criteria are the main methods used in proving the controller stability and smooth human-exoskeleton interaction. The challenges and future trend of this domain of research are discussed. Researchers can use this review as a basis for further development and exploration of other methods that assure the safety of the users of exoskeletons.

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