Review of Assistive Strategies in Powered Lower-Limb Orthoses and Exoskeletons

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Abstract

Starting from the early research in 1960s, especially in the last two decades, orthoses and exoskeletons have been significantly developed. They are designed in different architectures to assist their users' movements. The research literature has been more prolific on lower-limb devices: a main reason is that they address a basic but fundamental motion task, walking. Leg exoskeletons are simpler to design, compared to upper-limb counterparts, but still have particular cognitive and physical requirements from the emerging human-robot interaction systems. In the state of the art, different control strategies and approaches can be easily found: it is still a challenge to develop an assistive strategy which makes the exoskeleton supply efficient and natural assistance. So, this paper aims to provide a systematic overview of the assistive strategies utilized by active locomotion-augmentation orthoses and exoskeletons. Based on the literature collected from Web of Science and Scopus, we have studied the main robotic devices by focusing on the way they are controlled to deliver assistance; the relevant validations are as well included, in particular experimentations with human in the loop. Finally current trends and major challenges in the development of an assistive strategy are concluded and discussed.

Keywords: lower-limb, exoskeletons, orthoses, powered, assistive strategies

1. Introduction

The initial studies about lower-limb orthoses for motion assistance can date back to 1960s in Unites States [1] and in the former Yugoslavia [2], respectively with military and medical services purposes [3]. Since then, orthoses and exoskeletons have been developed prosperously, in different types of mechanical structures, actuators and interfaces. Nowadays they are addressed as tools to relieve the repetitive and heavy rehabilitation work of physical therapists while improving the (neurological or orthopedic) patient's recovery efficacy – Loko-Mat [4], LOPES [5]; they are also aiming to help paraplegic or quadriplegic people to regain locomotion ability in daily life – ATLAS [6], ReWalk™ [7], Ekso (Ekso Bionics, US, formerly eLEGs [8]); they are adopted as augmentation system empowering healthy people in order to perform heavy loads carrying – BLEEX [9], Sarcos Exoskeleton [10], MIT Exoskeleton [11]; they are also used to provide additional power for walking or stair-climbing of people suffering from muscular weakness (e.g. elderly persons) – HAL [12], HONDA Stride Management Assist (Honda, Tokyo, Japan). The latter emerging application field is a consequence of the population ageing in industrialized countries: the ratio of people older than 65 years reached 17.5% over the whole population in European Union in 2011, and is estimated to reach 29.5% in 2060 [13]. Similarly, in USA the over-65 population percentage was 13.3% in 2011, with an expected increase to 21% in 2040 [14]. Due to a low birth rate and high life expectancy in these countries, the ageing tendency will unlikely stop. This brings considerable attention, from both social and ethical points of view, on how to provide assistance for the elderly in their daily life, especially concerning mobility and autonomy. In an age where technology is becoming more human friendly, smarter and safer, development of self-standing lower-limb orthoses and exoskeletons for physical aid represents one of the most addressed mobility assistance option.

Recently published reviews give us the opportunity to obtain a general acknowledgement of these devices. In 2008, Dollar and Herr presented a study on the actuation, sensory and control systems of the most famous lower-extremity exoskeletons and rehabilitation orthoses, including full-body, modular and single-joint systems [3]; then another work provided an overview of the robotic system from the point of view of mutual arrangements between the device and the wearer, whether in series or in parallel [15]. Regarding the orthoses applications in post-injury or post-stroke gait training or neurological rehabilitation, it could be found in [16–19]; while an analysis of the mechanical design of knee-ankle-foot orthoses is depicted in [20]. Apart from the above works addressing multi-joint exoskeletons or orthoses, there is also other review literature presenting single-joint orthoses: the mechanical design of ankle foot orthoses (AFO) [21], and control algorithms for robotic ankle systems [22].

Although the above review papers are relevant to research topics of lower-limb wearable robots control, they lack a systematic analysis of the adopted assistive strategies in movement augmentation/assistance. Generally, the exoskeleton-human interaction is bidirectional: the robot provides mechanical power

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and feedbacks information to the human, and receives the intended movement from the user. While the former direction is more involved in a hardware level, the latter is more linked to a high level controller, i.e. a control layer which interprets the sensory information and decides when and how to deliver mechanical power to the user. The high layer controller could represent the core intelligence of a wearable robot and is defined as *assistive strategy* in this paper. The objective of this paper is to provide a systematic review of the *assistive strategies* utilized by powered lower-limb exoskeletons and orthoses and the related *experimental validation achievements*.

In particular, in this review paper we will address assistive strategies of lower-limb exoskeletons utilized to supply additional energy for daily-life movements of healthy young and elderly people and those suffering from lower-limb muscular weakness or disabilities. Reported studies will be categorized according to the high-level control strategy, not on the employed exoskeleton: from this point of view, the devices specifically addressing neuro-rehabilitation or gait-training – e.g. LOPES [5], ALEX II [23] – will not be included directly, since the rehabilitation treatment of these systems aims to override the user's volitional movements in order to help them recover from motor damages (in this way, the human-robot interaction is lowly bidirectional). Nevertheless, some of these systems could also be employed in a motion assistive paradigm (even if their usability is intrinsically limited by the frame-fixed mechanical architecture), and the related outcomes are reported in this work.

The paper is structured as follows: we firstly describe the literature searching methodology, and separate the collected papers into several categories. Then, we present the reviewed assistive strategies in accordance with involving multi-joint exoskeletons or single-joint exoskeletons. In the end, the state of the art of assistive strategies is concluded and the challenges in developing, tuning and validating an assistive strategy are discussed.

2. Literature Search Methodology

To get a collection of publications within our review scope, we performed a paper search on both Web of Science and Scopus, with a set of keywords involving six different topics:

Topic= (leg OR hip OR knee OR ankle OR foot OR (lower AND (limb* OR extremity OR body))) AND Topic= (power* OR active) AND Topic= (aid OR assist* OR improv* OR augment* OR enhance* OR climb stairs OR reinforc*) AND Topic= (ortho* OR exoskeleton* OR wearable robot* OR portable robot* OR robot suit) AND Topic=(control* OR validation*) NOT Topic= (post stroke).

With the above keywords, we originally obtained 723 papers (the literature research was updated till July, 2014): 428 papers from Web of Science and 295 papers from Scopus, with only 25 papers in common. It was possible to further exclude some results on the basis of their research fields: papers related to some peculiar medicine specialization fields but not linked to movement assistive technologies (e.g. physiology, surgery, veterinary, nutrition), papers from engineering research files but not addressing the exoskeleton control and assistance (e.g. prosthetics, material sciences, manufacturing), and a few papers belonging to completely unrelated fields (e.g. acoustics, optics, environmental sciences). In total, we were able to exclude 520 results, with the remaining 178 all written in English and published in journal or conference proceedings after 1990.

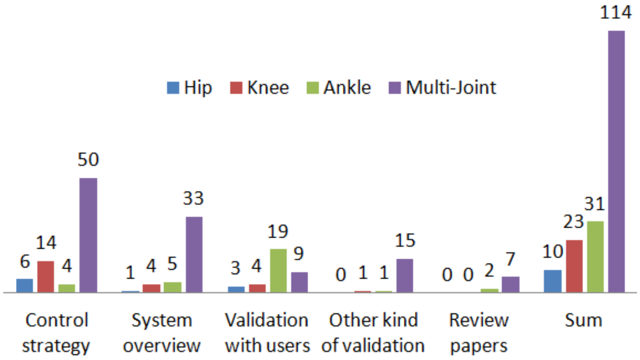

Table 1: Different categories of papers collected for the review

In order to extract the typologies of assistive strategies and the corresponding validations, the 178 papers were initially classified according to their main topics, in particular, the topic categories listed hereafter: Table 1 shows the numbers of papers belonging to each category, in which the results are further separated based on multi-joint exoskeleton, hip exoskeleton, knee exoskeleton and ankle-foot orthosis.

Control strategy: Papers mainly emphasizing the control algorithms. Papers belonging to this set constitute the main literature which allow us to identify different assistive strategy paradigms. Typically, these papers address a distinctive control strategy (e.g. sensitivity amplification, rather than fuzzy-logic-based control algorithm) and its implementation with a given device.

System overview: Papers introducing the structure and function of an orthosis, such as mechanical architecture, sensory and control systems. Each of the previous 'Control strategy' papers allows us to identify an assistive strategy utilized by a specific exoskeleton: a brief investigation on how the companion exoskeleton being built is mandatory for catching the key points of the assistive strategy.

Validation with users: Papers specifically presenting and analyzing experiments carried out with real subjects wearing the exoskeletons. Analyzing these papers is necessary to evaluate how the assistive strategy effects on users.

Other kind of validation: Papers addressing the mechanical design or the sensory apparatus of an exoskeleton, and their related characterizations, but without addressing human-in-the-loop experimentations. These papers are not of direct interest, unless they present the only experimental report about the investigated exoskeleton.

Review papers: Review works about powered lower-limb assistive exoskeletons and orthoses.

In order to retain citations which were latest updated or provided more explicit information about an assistive strategy, we further refined the bibliography set: among papers which presented similar strategies on the same robots and/or similar experimental validations (typically, a conference proceeding article and its journal extended version), we took into account only the more relevant works and only retained the exoskeleton descriptive papers with the higher level of technology maturation. At the end, 76 papers were kept to address assistive strategies applied by powered wearable robotic devices and related validation experiments.

In this paper, the reviewed assistive strategies were reported in respect of involving multi-joint or single-joint systems (Section 3 and Section 4): it is worth mentioning that this report frame does not refer strictly to the designed mechanical structure of an exoskeleton (which is usually adapted by previous review works), but rather specifies how many lower-limb joints are taken into account in order to implement the assistive strategy (hence facing their synergies in terms of forces and/or movements). In Section 3, among the multi-joint robotic systems, seven assistive strategy paradigms were recognized and reported in Subsection 3.1-3.7. In Section 4, the single-joint exoskeletons were further distinguished among hip, knee and ankle orthoses, and assistive strategies were reported respectively under these three categories.

3. Multi-joint Exoskeleton

Multi-joint exoskeletons have been developed for various purposes, such as providing extra locomotion energy for healthy young and elderly people, improving load carrying ability of soldiers or heavy labor workers, and aiding paraplegic or lower-limb impaired patients to regain independent mobility. Some multi-joint exoskeletons presented in this paper could be found in Figure 2 and Figure 3. According to the covered mechanical joints, multi-joint exoskeletons, here, are distinguished among trunk-hip-knee-ankle-foot (THKAF), hip-knee-ankle-foot (HKAF), trunk-hip-knee (THK), hip-knee (HK) or knee-ankle-foot (KAF) orthoses and exoskeletons, as shown in Figure 1.

In the upcoming Subsection 3.1-3.7, seven assistive strategies will be presented in which we have collocated the robotic devices from the analyzed literature. *Sensitivity amplification* control (Subsection 3.1) is more applied to THKAF exoskeletons to augment wearer's load carrying ability. *Predefined gait trajectory* control (Subsection 3.2) is easier to implement, but forces the user to walk in a reference gait which may be not natural. *Model-based* control (Subsection 3.3) is popular in various applications, but it needs an accurate modeling of the coupled human/exoskeleton dynamic system. *Adaptive oscillators-based* and *Fuzzy* controllers (Subsection 3.4 and 3.5) represent adaptive models which recursively follow user's intended movements, respectively relying on the periodicity of the gait pattern (hence extrapolating the future posture of the limbs) and on a preset fuzzy-logic layer. In a *predefined action based on gait pattern* (Subsection 3.6) control framework, the recurrent gait phase transitions are used to regulate the controller's action, resulting in a flexible interaction. *Hybrid assistive strategy* (Subsection 3.7) have been addressed in order to recognize an effective robotic control with two or more control methods.

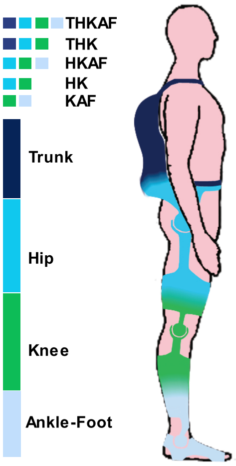

Figure 1: Different kinds of multi-joint exoskeletons.

3.1. *Sensitivity amplification*

The Sensitivity amplification is mostly used to handle exoskeletons which increase the load-carrying capability of a user. In this strategy, the controller relies on an inverse dynamic model of the exoskeleton; the force exerted by the wearer on the exoskeleton is set on a positive feedback loop of the controller and could be scaled down by an amplification parameter [24]. So this controller is distinguished from a traditional model-based controller which calculates the desired joints positions or torques directly. When the exoskeleton could accurately shadow the wearer's movement, the force exerted by the user will approach to zero. However, the controller could also amplify an external disturbance force, which makes the system become unstable. In case of destabilization occurring, the user has to promptly move him/herself in order to create a new stable condition of the whole system [25]. Moreover, this assistive strategy requires a high accuracy of the inverse dynamic model.

3.1.1. *Berkeley Lower Extremity Exoskeleton (BLEEX)*

BLEEX is the first load-carrying and energetically autonomous exoskeleton [26]. With an anthropomorphic design, BLEEX has a left and right three-segment leg, with segments analogous to the human thigh, shank and foot. Each leg has seven degrees of freedom (DOFs): hip flexion/extension (f/e) and abduction/adduction (a/a), knee f/e and ankle dorsi/plantar flexion (d/p) are active, while the others (hip intra/extra rotation, ankle inversion/eversion and a/a) are equipped with passive mechanical impedances (metallic or elastomeric springs).

The work [24] has presented an assistive strategy for BLEEX based on sensitivity amplification controllers. In this work, the inverse dynamics in sagittal plane is modeled differently depending on three gait phases: a full 7-DOF serial link mechanism for the single-support phase; two 3-DOF serial link mechanisms with one connection DOF along their uppermost link for the double-support phase; a 3-DOF serial link mechanism for the support leg and a 4-DOF mechanism for the redundant leg during late stance phase. The gait phases are distinguished by foot insole sensors. Under this control strategy, BLEEX could walk at an average speed of 1.3 m/s while carrying a 34 kg payload.

In recent years, military-used strength augmentation exoskeletons have been developed prosperously and reached or near to market application, for example, the Sarcos-Raytheon 'XoS' series (Raytheon, US, www.raytheon.com) and Human Universal Load Carrier (HULC) (Lockheed Martin, US, www.lockheedmartin.com). However, they are available only on media platforms without public scientific research results. As these devices are structurally similar to BLEEX, the sensitivity amplification control is as well supposed to be suitable for these devices.

3.1.2. Naval Aeronautical Engineering Institute Exoskeleton Suit (NAEIES)

NAEIES [27] is developed for heavy loads carrying on different kinds of terrains. There are six DOFs for each leg: hip f/e and a/a, knee f/e, and all the three ankle DOFs. Instead of relying on a very accurate exoskeleton inverse dynamics model, its control strategy is preferred to accept not-zero steady state value of the human-machine interface force, and to compensate it through a neural network [27]. Here, the human-machine interaction force is measured by multi-axis force/torque sensors.

Though the efficacy of the neural network compensation ability was validated by simulations on 1-DOF and 2-DOF systems, the limitations due to greater computing cost and extra sensors should be weighed carefully before a practical application which was not yet faced by the NAEIES researchers.

3.2. Predefined gait trajectory control

Under a predefined gait trajectory control mechanism, the desired joint angle is pre-recorded from a healthy person, or extrapolated from a gait analysis data atlas, and then replayed on an exoskeleton. To improve usability and flexibility of the controller, the desired joint trajectory is usually parameterized according to different postures. In our studied literature, this kind of assistance mainly targets subjects partly/completely losing normal voluntary movements, for example ATLAS (3.2.1) aims at quadriplegic children, HAL (3.2.2) could be used by gait disorders patients, ReWalk$^{\text{TM}}$ (3.2.6), eLEGS (3.2.7) and Vanderbilt Lower-Limb Exoskeleton (3.2.8) are suitable for SCI patients. For proof of concepts, validation results with healthy subjects are also presented with some robotic devices dedicating to paraplegic patients, e.g. IHMC Exoskeleton (3.2.3), MINDWALKER (3.2.4), Walking assistance device by T. Ikehara et al. (3.2.5).

3.2.1. ATLAS

The ATLAS project aims to deploy an active orthosis for gait assistance, in particular focusing on children suffering from quadriplegia [28]. The first prototype of the ATLAS exoskeleton provides active motion for the hip and knee f/e, with the ankle f/e under-actuated by connecting to a linkage between the thigh and shank. Considering the targeted end-user, ATLAS aims to be a totally autonomous assistive orthosis, with the wearer only giving locomotion maneuver triggers, e.g. start and stop, stand up and sit down.

In the latest studies [28], ATLAS employs two finite-state machines to separately tune the hip and knee joints trajectories recorded from healthy children. During stance phase, the hip follows a parameterized inverted pendulum trajectory in which the height and the stride lengths are configured to fit the subject's physical characters. During early swing, a constant torque is applied to both the hip and knee joints until each limb reached its preset speed. In the middle of the swing, the hip and knee move freely, requiring almost no torque. At the end of the swing phase, a position controller is used to make the joints reach the desired posture at heel strike. While in another work [6], the swinging leg trajectory follows a parameterized pendulum model. The transition trajectory between stance phase and swing phase is smoothed with a Gaussian function based filter.

In the above two cited works, there is not a detailed description of involved experimental validations, but the videos referred in [6] have shown two quadriplegic children successfully moving inside ATLAS.

3.2.2. Hybrid Assistive Limb (HAL)

HAL is developed to physically augment joints power of healthy people, or assist people affected by gait disorders to move and execute everyday's life activities as healthy individuals [12]. Different types of HAL have been developed: a HKAF orthoses, a whole body and also a single-leg device. All types provide motion assistance on the sagittal plane, i.e. to the f/e and d/p DOFs. When HAL targets to aid people having difficulties in walking, an autonomous controller is used to provide assistance on the hip and knee joints while the ankle joint behaves passively as a spring [12]. The hip and knee joints of HAL are controlled based on two gait phases: swing phase and support phase. The desired joints patterns are pre-recorded from a healthy subject and are allocated to these two phases by a real-time intention estimator (understanding user's start walking, stop walking, leg swing) which counts on floor reaction force and torso angle [29].

This assistive strategy was validated with two subjects: one was with lower-limb sensory paralysis and another one was healthy but simulated to have both sensory and motor paralysis on two legs. Only kinematics results were analyzed and proved the feasibility of the whole system as well as the reliability of the intention estimator [29].

3.2.3. IHMC Mobility Assistive Exoskeleton and Mina

The IHMC Mobility Assist Exoskeleton presented in [30] has three actuated DOFs on the hip a/a and f/e and knee f/e, and two passive DOFs on the hip rotation and ankle d/p. Thanks to the anthropomorphic design and its series elastic actuators (SEA) [31], the IHMC exoskeleton could work in different modes, like zero assistance mode, performance augmentation mode, and gait rehabilitation mode. Of all, its primary goal is to successfully enable a person with lower-extremity paralysis to walk in a straight line for a distance of 15 feet. Because the hip a/a is not demanding during a straight line walking, its joint is replaced with a rigid link. Joint trajectories for the hip and knee f/e are recorded from the gait of a healthy people wearing IHMC in zero assistance mode. When trajectories are replayed in realtime practice, the wearer has to collaborate with the exoskeleton dynamically: wear has to unload the upcoming swing leg by adjusting his/her torso position.

Four able-bodied users tested IHMC with one recorded gait pattern [30]. During experiments, they were asked to totally relax their leg muscles. All of them were able to walk a short distance at full trajectory playback speed, but they needed crutches to keep balance.

Mina is a second version of the IHMC exoskeleton [32], with only two actuated DOFs: hip f/e and knee f/e, and a more compact mechatronic architecture. It is aimed to provide mobility assistance for people suffering from paraplegia or paraparesis. Its control method is similar to the earlier IHMC version, moving the user's legs by replaying pre-recorded joints trajectories. Wearing Mina the user can trigger single step or continuous steps, as well as increase or decrease the walking speed. To help users get familiar with Mina, step transition duration can be tuned as well. Two SCI subjects evaluated Mina: after different training sessions, both of them were able to walk with forearm crutches at speeds up to 0.20 m/s. Their cognitive efforts were evaluated to be low, since they could maintain eye contact and converse while walking in Mina.

3.2.4. MINDWALKER

MINDWALKER is a powered THKAF exoskeleton designed for paraplegics to regain locomotion capability [33]. It has five DOFs at each leg, with hip f/e and a/a and knee f/e powered by SEAs, while hip rotation and ankle d/p passively sustained with a fixed stiffness.

The gait assistance in both lateral and sagittal plane is provided under nine states, defining the motion of left and right legs separately and coordinately. The state transitions are triggered in two types: stop-start walking and step-to-step transitions are triggered by the user command, while transitions from stance to swing to double stance are automatic. In sagittal plane, during swing phase, the hip and knee joints trajectories are predefined by recording the gait patterns of a healthy people walking with MINDWALKER in zero assistance mode; during stance phase, the joints trajectories are also predefined to keep the user-exoskeleton system in a equilibrium posture. In lateral plane, before toe off, the hip a/a joints shift the Center of Mass (CoM) to the stance side, and move back to their zero positions before heel strike. To prevent the user falling sideways, the hip a/a is also adjustable online by using an XCoM algorithm (extrapolated CoM, suggesting a simple form to enable balance walk) [33].

Six healthy and four SCI participants were involved in ground-level walking experiments wearing MINDWALKER [34]. To keep balance, the SCI patients needed to hold the handrail: electromyography (EMG) patterns of their upper-limb muscles were measured and showed to be augmented for stepping, while leg muscles were lowly activated if any. In healthy subjects, EMG activities of leg muscles were similar or even larger during exoskeleton-assisted walking compared to free level walking, but smaller than walking under not-assisting mode.

3.2.5. Walking assistance device by T. Ikehara et al. [35]

The HKAF walking assistance device described in [35] aims at aiding elderly and impaired people. Its actuation system is placed in a backpack, with transmission employing flexible shafts: the torques effectively applied to the active joints – knee and ankle – are calculated on the basis of the shaft twist angle. The desired joints angles and torques are referred to gaits data of healthy people. Rather than tracking only one kind of desired signal, only angles or only torques, the actuators' final outputs are determined by hybridizing the joints angles controller and torques controller with a certain ratio (experimentally chosen).

Walking experiments have been carried out with both healthy subjects and paralyzed subjects [36]. EMG activities measured from one healthy subject showed a decreasing muscular activity with respect to normal walking without the orthosis. In the experiments with paralytic patients, the device only applied assistance to their ankle joints. Still, their hip kinematics were found to be affected: averagely, the hip f/e motion was decreased by about 7.4% than non-assistance walking, while the maximum hip internal/external rotation angle was reduced 15% compared with non-assistance walking.

3.2.6. ReWalk™

ReWalk™ is a powered exoskeleton to assist individuals with thoracic-level complete SCI to walk independently [7]. Its hip and knee joints are powered and controlled to follow a predefined trajectory. With a wrist-pad controller, the user can activate the robotics system to perform stand, sit or start walking; with a torso tilt sensor, the user can trigger step to step transition during walking.

Twelve subjects with chronic motor complete cervical and thoracic SCI have been trained to use ReWalk™ [37]. After eight weeks of practicing, all subjects were able to walk independently with crutches, without any other human assistance, for at least 50 meters continuously, for a period of at least 5-10 minutes continuously and with velocities ranging from 0.03 m/s to 0.45 m/s. Their gaits were fundamentally symmetric.

3.2.7. eLEGS

A THKAF exoskeleton, eLEGS, is developed to support patients who have difficulties in lower-limb functions of sitting, walking, and standing [8]. Its hip and knee f/e are actuated, while ankle d/p is passively actuated with a spring. A finite state machine is used to determine the movements of the two exoskeleton legs. During walking, one stride cycle is separated into four states: left swing, left double stance, right swing, and right double stance. Stance to swing transition is triggered by the user moving his/her crutches and shifting his/her body weight; swing to stance transition is triggered by heel strike detection. In sitting down and standing up maneuvers, the two robotic legs are actuated symmetrically with the same trajectory: even though, each leg is controlled separately.

Five subjects with varying SCI levels and completeness tested eLEGS and all of them were able to quickly learn to use the machine to deploy consistent cadences [8].

3.2.8. *Vanderbilt Lower-Limb Orthosis*

The Vanderbilt HK orthosis is designed to assist the hip and knee f/e of SCI individuals [38]. To help the user keep ankle stable during stance phase and avoid drop foot during swing phase, the Vanderbilt orthosis could be mounted with a standard AFO. For a safety reason, the knee joints are equipped with normally locked brakes in case of power failure. The orthosis controller consists of four motion states: standing, right forward, left forward, sitting [39]. In each state, the joint angle are pre-programmed based on recorded trajectories from a healthy subject wearing the inactive orthosis. Switching between states is initiated by user's vocal command.

This assistive strategy was experimentally implemented on a complete spinal cord injury (SCI) paraplegic subject walking with handrail. The subject could walk with an average speed of 0.8 km/hr, and kinematics results analysis indicated a high degree of step-to-step repeatability of hip and knee trajectories.

In a stair climbing application [40], the orthosis motion is divided into two sequences to lift two legs one after another in a predefined manner. Each sequence is triggered based on the position of Center of Pressure (CoP). Unlike stair ascent, the stair descent procedure requires only an initial CoP trigger. In the involved validation experiments, a paraplegic subject with a T10 complete injury did succeed in ascending and descending a standard staircase with handling external supports.

3.3. *Model-based control*

Under a model-based control structure, the desired robotic action is computed on the basis of a human-exoskeleton model, usually considering gravity compensation, zero moment point (ZMP) balance criterion, and providing extra commanded assistance. Though being straightforward, this control strategy relies on the accuracy of the model which requires series of sensors to recognize kinematics and dynamics variables. The following reported robotic devices are used in different purposes, for example HAL (3.3.1) and ABLE (3.3.2) target at assisting paraplegic subjects daily-life movements; BE (3.3.3) and Nurse Robot Suit (3.3.4) can augment the wears staff-holding capability; WWH (3.3.5), WPAL (3.3.6) and XoR (3.3.7) are mainly suitable for muscular weakness people.

3.3.1. *HAL*

As introduced in Subsection 3.2, HAL is developed to aid people moving and executing daily-life activities. In [41], a model-based assistive strategy is proposed, in order to mainly support the knee flexion for persons with motion difficulties but whose EMG signals can still be detected from the knee flexor. The total knee flexion torque basically includes three components: an assistive torque to drive the knee joint, a viscous torque providing a damping effect and a gravity compensating torque calculated on the basis of a static lower-limb HAL-human model. The motion support of HAL is activated consistently with the user's motion intention which could be estimated by the knee flexor bioelectrical signals.

A 60-year-old male subject with impairment on the right knee participated in the validation experiments [41]. The trials were carried out in standing posture: firstly the subject shifted his weight completely to the left, then as soon as bioelectrical signals were detected, the right knee bent; when the right knee joint was flexed to a preset angle, the torque was released, and the subjects extended his right knee by himself and brought his weight on his right leg. Results of repeated trials have shown that with HAL the impaired knee joint was effectively assisted in flexion and that the muscular activity was also reduced.

In [42], HAL is used to support a paraplegic patient to perform sit-to-stand and stand-to-sit. The assistance is based on balance control and gravity compensation, both of which are designed according to a static human-HAL model. Each motion is divided into a series of phase sequences and is triggered based on a preliminary motion of their upper body. The related clinical experiment was to assist a 66-year-old male with complete SCI to complete sit-to-stand and stand-to-sit transferring. However, he had to hold the parallel bar to keep balance. HAL could successfully detect his sit-to-stand and stand-to-sit intentions, and provide motion supports.

3.3.2. *ABLE*

ABLE is a moving transfer system for subjects with impaired lower limbs. It consists of a powered lower-limb orthosis, a pair of hand crutches and a pair of foot mobile platforms to assist the wearer traveling in a standing posture, standing up from a chair, and stair ascending [43]. The user could be supported by the orthosis, keeping balance by holding the crutches and traveling around by standing on the left and right moving platforms.

The desired torques from the orthosis and the desired movements of the mobile platforms and crutches are determined based on a quasi-static human-ABLE model. Their cooperation is defined according to different maneuvers. For example, during straight motion, all angles of the orthosis are fixed, and the mobile platforms propel the user moving forward; during turning around in standing posture, the orthosis lifts the user's legs and the mobile platforms rotate; during standing up/sitting down and stair ascending-descending, the orthosis provides assistance on the hip and knee joints based the model and cooperates with the crutches movements.

The work in [43] presented ABLE allowed a man with no leg motion to perform standing up, passing through a tiny gate, and traveling in straight line stably.

3.3.3. *Body Extender (BE)*

The BE is an advanced power-augmenting full-body wearable robot for handling heavy objects [44]. Like BLEEX, the weight of the payload is transferred to the ground through anthropomorphic legs. It has twenty-two independently actuated DOFs, with six DOFs on each leg. The primary trial on BE

Figure 2: BLEEX [26], ATLAS [6], HAL [12], Mina [32], MINDWALKER [33], ReWalk™ [37], eLEGs [8], Vanderbilt lower-limb orthosis [39].

control is based on its analytical model, which considers its kinematics and dynamics characteristics, the force exchange between the human and BE and the environmental force besides.

According to the work presented in [45], the exoskeleton trunk was assumed as attached to a rigid base and only simulations were performed on upper limb holding a heavy load.

3.3.4. Nurse Robot Suit

The Nurse Robotic Suit [46] is a full-body pneumatically powered exoskeleton designed to supply nurses with extra forces to lift their patients and avoid back injury. When the nurse stands up, the weight is transferred to the ground; when the nurse bends the waist or the knee, the total weight is supported by the actuators. The necessary joints torques are calculated based on a simplified static model. The pneumatic muscle forces driving the elbow, waist and knee joints are used to: compensate the whole system's gravity, which is calculated based on a simplified model; and the repelling force exerted by the nurse, which is measured by muscle hardness sensors.

Assistive efficacy was proved by executing a holding and up-down moving of a 60-kg-weight person [47].

3.3.5. Wearable Walking Helper (WWH)

WWH is a wearable gravity-compensating HK exoskeleton developed to assist the locomotion activities of disabled and elderly people [48]. The assistive torques provided by WWH are proportional to the torques calculated based on an approximated human body model, accounting user's posture and motion. Experiments with a subject standing up and sitting down showed a reduction of EMG activities at the rectus femoris, thus proving the WWH efficacy as an antigravity exoskeleton. In [49], pace changing and climbing/descending stair experiments were implemented with the same assistive strategy: heart rates were recorded and showed a reduction when the subject's movements were supported by WWH.

3.3.6. Walking Power Assist Leg (WPAL)

WPAL [50] is a wearable HK exoskeleton, developed to provide assistance to people with walking disorders due to aging, paralysis, or following amputation. WPAL realizes a compliance control using joint angles, velocity and interaction forces information, provided by a wide sensory apparatus, including force sensors on the thigh and lower leg and encoders at joint angles. The controller bases on dynamic models of the WPAL and the user's leg respectively, which are then analyzed synthetically to calculate demanded torques. Only bench test addressing the system's compliance was performed.

3.3.7. eXoskeleton Robot (XoR)

The XoR prototype has been developed for postural control of elderly people and persons with mobility disability [51]. XoR implements a hybrid driving concept combining pneumatic artificial muscles and electric motors together [51, 52]: the former acts as a gravity balancer while the latter as a dynamic compensator. The total generated torque tracks a desired value calculated on the basis of a bio-mechanical model. The user's posture is given by joint angles and ground reaction forces while the motion intention is estimated based on EMG signals. Only simulation results were available to prove the efficacy of this assistive strategy working with XoR.

3.4. Adaptive oscillators-based control

An adaptive frequency oscillator learning mechanism is firstly developed by Righetti et al. [53], in order to synchronize with the instantaneous frequency and phase of any periodic input signal. This model has been widely used in robotics field, for example, as a central pattern generator [54]. Ronsse et al. [55] extend this concept to the wearable robotics researches, with the aim of capturing periodic bio-signal features (i.e. phase, frequency, amplitude, offset) in walking or cyclic rehabilitation exercises. Besides the adaptive frequency oscillators, there are also some applications of traditional neural oscillators for their synchronization and inhibition properties [56]. In recent years, adaptive oscillators-based control is obtaining greater attention, however, in our literature review, it is found that its application is limited to subjects who can deliver periodic and stable bio-signals, and mostly validated on the hip joint actuation (referring to 4.1.1, hip exoskeleton).

3.4.1. Lower-limb exoskeleton by N. Tagliamonte et al. [57]

The treadmill-based lower-limb exoskeleton presented in [57] has a HK mechanical structure, with its weight compensated by an external support system. Though targeting at rehabilitation by providing assistance on the hip and knee joints in sagittal plane, in [57] the assistance is provided in order to augment the hip and knee f/e performance in walking. A pool of adaptive oscillators are utilized to track the fundamental frequencies of hip and knee angles and coupled with a non-linear filter to predict the next angles values. The desired torque is to attract the joints to their next status.

A healthy volunteer tested the stability and feasibility of the controller by walking on a treadmill with the exoskeleton: however, the effects of the assistance were not validated quantitatively, even if the the participant did not report any discomfort.

3.4.2. Full body exoskeleton by T. Matsubara et al. [58]

In [58], a control strategy based on style-phase pattern generation with oscillators is proposed. This strategy has been targeted to be implemented on a full-body exoskeleton robot for daily-life walking assistance of able-bodied persons or persons with weakened muscles. Instead of only considering joint kinematics, the controller also integrate the diversity of walking styles and CoP trajectory into the adaptive oscillators model and then determine the joints trajectories.

Simulation experiments with a 1.58 m, 60 kg, and twenty-two DOFs body model proved the feasibility and stability of this method.

3.4.3. Robot suit by X. Zhang et al. [59]

The walking assistance robot suit has four actuators for the hip and knee joints motion in the sagittal plane [59]. In its control system, mutual joint torque between the suit and human is fed as an input to a series of neural oscillators, serving for the synchronization between suit and human, and then the oscillators return the suit's desired joint angles. In [60], in order to provide assistance on hip joints and keep a anti-phase relationship between left and right hip joints, a mutual inhibition between left and right oscillators is as well incorporated into the control system.

Experimental validations were carried out under three scenarios: free walking without robotic suit, cooperative walking (wearing the robotic suit) with and without mutual inhibition between left and right neural oscillators [60]. Ten subjects attended the experiments. For the sake of simulating gait disturbance, a load was tied to the right ankle. All the subjects should walk back and forth in a room for one min along a five meters route. Activities of four muscles from the back and front of thigh and mutual joint torque between the suit and human were measured for each walking pattern. The experiment results showed a reduction of muscles activities and an increase in the step length and speed. Psychological evaluation with subjects showed that walking pattern with robot suit and mutual inhibition was considered as the easiest task, while walking with the Robot Suit without inhibition was the most unstable.

3.5. Fuzzy control

When it is difficult to structure an accurate dynamic model, a fuzzy control could be taken into consideration, in order to represent and implement an intuitive knowledge about how to handle a physical system [61]. A fuzzy controller consists of four main blocks: the fuzzification block, which interprets the inputs; the fuzzy-rules block, which holds the knowledge of how to control the system; an interface mechanism to select which rule should be implemented; and the defuzzification block which converts the fuzzy results into desired output signals. Fuzzy controller, however, requires many variables to be tuned manually according to the specific motion tasks and individuals [62]. In this study, only two devices specifically addressed this control method, one is the Lower-limb motion assist exoskeleton by H. He et al. (3.5.1) aiming to assist people affected by physical weakness, and another is EXPOS (3.5.2) aiming to assist elderly people in task of ground-level walking.

3.5.1. Lower-limb motion assist exoskeleton by H. He et al. [63]

The HKAF lower-limb exoskeleton presented in [63] has been designed to assist the movements of physically weak people. It consists of one passive DOF for the ankle d/p, and two active DOFs for the the hip and knee f/e joints. The desired assistance for hip and knee movements are estimated through an EMG-based neuro-fuzzy controller. In their study, eight kinds of EMG signals (from eight muscles on the thigh) are used to assist various moments, e.g. sitting down, standing up, climbing stairs and squatting. When the EMG levels are low, the input variables for the neuro-fuzzy controller are knee and hip forces; when the EMG levels are high, the input variables are switched to the EMG signals. As muscles have different performance in different persons and postures, the parameters of the fuzzy controller have to be configured carefully.

Experiments with a healthy male performing sitting down, standing up and squatting movements with and without assistance were carried out. Results showed the effectiveness of this controller, i.e. the EMG levels were reduced while hip and knee angles being controlled smoothly.

3.5.2. Exoskeleton for Patients and The Old by The Sogang University (EXPOS)

The tendon-driven HK exoskeleton system EXPOS is developed to assist patients with motion disability and elderly people [64]. EXPOS is accompanied by a smart caster walker carrying part of the heavier components, as motors, drivers, controllers and batteries, in order to keep the wearable device lightweight and simple. Drivers on the caster could actuate joints through a cable-pulley transmission. The assistance desired from EXPOS is computed by a fuzzy controller which is based on the joint angular velocity and torque. The fuzzy rules are configured on the basis of the joint angle and torque signals: in order to reduce disturbances, the output of the fuzzy controller always depends on the larger signal; when the two signals have the same direction, the fuzzy controller has the maximum output. The output of the fuzzy controller is defuzzified by using an interpolation method.

An elderly subject executed sitting down and standing up exercises with and without the help of EXPOS: the outcome was that 32% of muscular power was reduced with the EXPOS assistance.

3.6. Predefined action based on gait pattern

There are some exoskeletons providing assistance based on passive springs or pneumatic cylinders – systems with a physical impedance and compliance – controlled only by means of the activation and/or enrolling of these elements. Distinguished from the predefined trajectory control (Section 3.2), in which the system continuously tracks a prerecorded joint trajectory, this assistive strategy controls the device to act synchronically with expected gait events, for example, the pneumatic actuator on/off switch in Pneumatic active gait orthosis by G. Belforte (3.6.1) and in Power assist wear by D. Sasaki (3.6.2), the position of Bowden cable in Soft Exosuit (3.6.3), and the damper mechanism on/off in MIT Exoskeleton (3.6.4). The desired assistance in these devices depends not only on the time of the control command, but also on the characteristics of the elastic elements (stiffness, inertia, damping).

3.6.1. Pneumatic active gait orthosis by G. Belforte [65]

This is a the earliest pneumatic gait orthosis among the literature we have reviewed in this paper [65]. It is designed for gait rehabilitation as well as locomotion assistance for paraplegic subjects. This orthosis is composed by a commercial lower-limb passive support structure and a pneumatic actuation system which powers the hip and knee f/e movements. Pneumatic actuators are controlled by solenoid valves: the maximum orthosis flexion angle is a function of the cylinder rod stroke, while the f/e speed can be varied separately by means of air flow regulators. The on/off control of valves for each joint are predetermined by referring to clinical gait data.

Evaluation experiments were done on a bench test without user, with a healthy user and with a T3-lesion-level paraplegic subject. During experiments, the coordination between human and orthosis depended on the user, i.e. the user had to be trained in order to adapt to the orthosis. Both healthy and paraplegic subjects could walk with assistance, but from the kinematics and kinetics results shown in the paper, the orthosis was not proved to be adaptive and the signals were not smooth, especially the performance of paraplegic subject.

3.6.2. Power assist wear by D. Sasaki [66]

In [66], a trousers-like power assist wear for locomotion assistance is presented. The pneumatic actuators are composed by balloon and circular actuators which are attached by a hook-and-loop fastener between the outer and inner wears. According to the prototype figure, there are three actuators mounted on each leg: one on the knee, one on the back of the thigh and one at the back of the shank.

The expansion forces from actuators are applied to the knee joint through the extensible cloth attached on the outer wear. During leg swing, the inner pressure of actuators is decreased to make the leg move freely; during stance phase, the pressure is kept high; and when the heel leaves/contacts the ground, the pressure is increased. The gait events are detected with insole sensors. The torque executed on the knee is affected by the quality of the balloon and circular actuators which are characterized to be linear to the knee angle.

Experiments testing stair ascent and descent tasks were carried out with one subject. The subject's EMG showed decreased peaks during walking upstairs, but still some extra peaks were recorded while walking downstairs.

3.6.3. Soft Exosuit

In [67], a soft cable-driven THKAF Exosuit is presented. Differently from traditional exoskeletons, the Exosuit does consist of a rigid frame but a series of webbing straps, and uses geared motors to pull Bowden cables which are connected to the suit in proximity of the ankle. The activation of the cable is to provide assistance during the foot propulsion. When the cable is actuated, the heel is pulled upward and the bottom of the Exosuit is pulled downward. As a result, the suit tension is augmented and torques acting on the hip and knee joints are as well increased because of the curved path of the straps. When the cable is not actuated, the Exosuit forces can also be generated passively in the elastic fabric webbing due to the natural kinematics of walking. The position trajectory of the cable is predefined as a function of the gait percentage.

Primary results with a healthy subject showed that the Exosuit could apply powered torques to the hip and ankle joints, around 18% of the normal human walking torques.

3.6.4. MIT Exoskeleton

The MIT Exoskeleton, including THKAF, is designed for load-carrying augmentation by transferring the load of the back-pack to the ground through a pelvic harness. In [68], the hip and knee f/e are both powered, while in [11], only the knee joint, with a damper, is actively controlled.

The actuation of the hip and knee joints is a function of the gait cycle, and the desired assistance is determined by referring to human walking data [68]. The gait cycle is divided into different states, including not walking, and each state is triggered in accordance with joints angles, joint torques and ground reaction forces. In general, a propelling positive power acts on the hip joint to help raise the CoM during the early stance phase; energy stored during late stance phase is released for the swing phase. The damper mechanism at knee joint is turned on at heel strike and turned off at the end of stance to allow knee flexion.

Experiments with the active hip and knee joints version have shown that the exoskeleton could transfer 90% of payload to the ground. Experiments with only knee being actively controlled proved the load carrying efficacy, though the measurements of transport metabolic cost showed an increase with the exoskeleton, compared to freely carrying a standard loaded backpack [68].

3.7. Hybrid assistive strategy

Hybrid assistive strategy aims to control the exoskeleton by applying different assistive strategies: BLEEX (3.7.1) adopts a sensitivity amplification controller in swing phase and a position controller in stance phase; Pneumatic muscles orthosis by T. Yeh et al. (3.7.2) utilizes a model-based controller in stance phase and a predefined trajectory controller in swing phase; the

AIT leg exoskeleton-I (3.7.3) firstly predefines the gait trajectory offline and then uses a fuzzy controller to adjust the trajectory online. For a specific gait state, the efficacy of assistance could be improved. However, the transition between each strategy should be taken into account to avoid discontinuity or uneven outputs.

3.7.1. *BLEEX*

In another work, BLEEX is controlled by means of a hybrid controller [69]. During swing phase, the exoskeleton leg is controlled by a positive feedback sensitivity amplification controller. When the leg enters stance phase, a position controller is enabled, with the desired torque proportional to the differences between human joint angle and BLEEX joint angle. The two legs are controlled independently and the switch between the two controllers is decided according to the gait states. The successful implementation of the stance-phase position proportional controller is due to the compliant mechanical connection mechanism between the pilot and BLEEX.

With this hybrid assistive method, experiments demonstrated that a pilot could walk in BLEEX at 0.5 m/s with a payload of 18 kg: however during the experiments, pilot needed to hold a handrail to keep balance, and BLEEX performances were lower than in the case of the only sensitivity controller.

3.7.2. *Pneumatic muscles orthosis by T. Yeh et al. [70]*

A KAF powered lower-limb orthosis for assisting elderly or impaired people walking and climbing stairs is presented in [70]. The knee f/e is actuated with a pneumatic muscle, while the ankle joints are passive. A hybrid controller based on gait phases has been designed. In stance phase, the desired knee support torque is calculated with an inverse model. During leg swing, a reference trajectory extracted from a healthy person is used to lead the knee extension. Each state is activated by shoe pressure sensors and the assistance transition between these two states are smoothed with two anti-windup compensators [70].

A healthy subject addressed both walking and climbing stairs in order to validate the orthosis and the control strategies: assessment was conducted through the recoded EMG activities from quadriceps muscles. During level walking trials, EMG activities were reduced by 36% when an assistive torque was exerted. During ascending and descending stair trials, the EMG activities were decreased by 33% and 26.1% respectively.

3.7.3. *Asian Institute of Technology (AIT) leg exoskeleton-I*

AIT leg exoskeleton-I [71] is developed with the purpose to assist patients suffering from immobility of lower limbs, mainly paraplegia. It has three DOFs at the hip, one DOF at the knee and two DOFs at the ankle, controlled by twelve DC motors.

The joints trajectories of AIT leg exoskeleton-I are generated offline basing on its dynamic kinematic model. To ensure balance, the model adopts the zero moment point (ZMP) criteria, providing an estimation of the ZMP location. In real-time use, the real-time ZMP is estimated by a ground contact point method. To compensate disturbances and uncertainties, the differences between real-time ZMP and reference ZMP are fed to a fuzzy-logic controller, based on which the ankle roll and pitch angles are adjusted correspondingly. This balance keeping strategy was only validated on bench test with a simplified human body model.

4. Single-joint Exoskeletons

Lower-limb single-joint exoskeletons are easily to be divided into hip, knee or ankle systems. The role of these joints is fundamentally different [72]: in level walking, knee is mostly a free-damping joint in the swing phase, while almost locked during the stance phase; hip and ankle are mostly related to the swing dynamic handling and the stance-phase ground propulsion, respectively, but more recent researches have also showed their mutual dependence. In all of the following cases, the addressed DOF is always the sagittal plane joint, thus the f/e (or the analogous d/p, for the ankle) one. Some examples of the single-joint exoskeletons presented in this section are shown in Figure 4.

Among single-joint devices, there are two additional assistive strategies which are not found in the multi-joint-exoskeletons: the *muscle stiffness* control and *proportional myoelectric* control. They are applied only in single-joint devices, since they need reference muscles to set the level of assistance: multi-articular muscular systems make their implementation on a multi-joint exoskeleton more complicated. The difference between the two strategies is the kind of bio-signal used to estimate the muscular action, respectively an external pressure sensor and an EMG detector. Conversely, the sensitivity amplification, the fuzzy control and the hybrid control did not appear among the assistive strategy family used by single-joint devices.

4.1. *Hip Exoskeletons*

4.1.1. *Adaptive oscillators-based control*

LOPES. The work from R. Ronsse et al. [55] is the first application of adaptive oscillators on a lower-limb assistive exoskeleton, LOPES. LOPES is a THK frame-based treadmill-mounted exoskeletons with actuated hip f/e, a/a and knee f/e [5]. It is put in the single-joint system section, since the adaptive oscillators-based assistive protocol tested with this exoskeleton is only applied to the hip, without any influence from the other lower-limb joints, nor with the help of ground reaction forces sensors.

The control is realized in a model-free mode: in real-time operation, a pool of adaptive oscillators are adopted to extract the phase and frequency of hip joint angle. Then the phase and hip joint angle are fed to a kernel filter estimating the predicted hip joint angle without delay. The desired joint torque is computed as to attract the hip joint to its predicted angular position, by multiplying the difference between predicted and current hip joint angles with a virtual stiffness. This assistive strategy requires no extra sensors except the encoders, already integrated in the exoskeleton.

Nine healthy participants took part in the experiments evaluating this assistive strategy, in which they walked on the treadmill in four modes: free walking, walking with LOPES without assistance, with a low assistance and with a high assistance

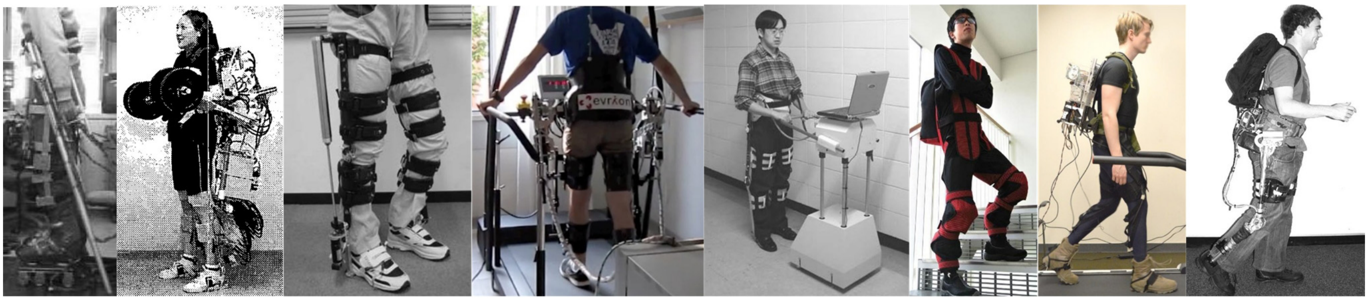

Figure 3: ABLE [43], Nurse Robot Suit [47], WWH [49], Full body exoskeleton by T. Matsubara et al. [58], EPOS [64], Power assist wear by D. Sasaki [66], Soft Exosuit [67], MIT Exoskeleton [11].

(by making the virtual spring stiffer). Energy expenditure was recorded and analyzed. With assistance, energy consumption was lower than in the no-assistance mode, but higher than the free walking condition. However, in assisted walking condition the energy expenditure tended to be more reduced at the very end of the walking, indicating that the subject could benefit more of the assistance from the exoskeleton after an adaptation period.

ALEX II. It is a treadmill-based THK unilateral exoskeleton, whose weight is supported by an external frame [23]. Similarly as what is done with the LOPES, ALEX II is used as an hip f/e assistive device, purely basing on the hip joint characteristics [73], and these results are hence collected in the single-joint section. In this use, the control paradigm aims to exert a hip torque based on online gait analysis results, with the current percentage of gait cycle furnished by the adaptive oscillators: the gait stride initiation is detected by a foot-pressure, then an adaptive frequency oscillator is utilized to track the hip joint angle signal and extract its periodicity features, detecting also the instantaneous walking speed. By combining these two information, the instantaneous stride cycle percent is computed out. The output torque at each stride percentage, and at a certain cadence, is decided by referring a 2D lookup table interpolating the hip joint torque profiles reported in Winter dataset [72].

This assistive strategy has been validated with ten healthy subjects walking under three conditions at 2.4 km/h: free-walking mode, zero torque mode and assistive mode. During the experiments, the EMG activities from six lower-limb muscles were measured and showed a lower envelope in assistive mode than in the other two conditions. The EMG analysis results also demonstrated that the ankle muscles could benefit from assistance provided on the hip joint.

One-DOF exoskeleton device by G. Aguirre-Ollinger [74]. In this work an assistive strategy based on adaptive frequency oscillators for the hip movement assistance has been proposed. The implementation of this algorithm requires two stages: the extraction of the EMG envelope, and the online provision of the assistive action. Firstly, the EMG signal and hip joint angle are recorded synchronically. The hip joint angle signal is tracked by a pool of adaptive frequency oscillators, extracting its instantaneous phase online. The EMG signal, after an offline post-processing, is reconstructed with a locally weighted regression method to be a function of the adaptively learned gait phase. Then in real-time assistance delivering mode, controller generates assistive torques by scaling the prelearned EMG envelope along with gait phase being estimated online by adaptive oscillators.

Two male participants performed uniform leg swing movements on a 1-DOF exoskeleton device for thirty seconds, with and without assistance. Results showed that the actuator output torque was timely coordinated with the EMG activities.

4.1.2. Model-based control

Parallel hip joint exoskeleton by Y. Yu et al. [75]. This bilateral hip joint exoskeleton is arranged in a parallel kinematic chain fashion, and consists of a 6-DOF (f/e, a/a, rotation for both hips) platform, with three serial universal-prismatic-spherical chains per side, surrounding the user hip articulation. Expected velocity is calculated based on the a kinematic model of the parallel manipulator.

The applicability of this controller was proved through simulation results and experiments where the end-effector was manually moved along a preset trajectory.

4.1.3. Predefined action based on gait pattern

Hip orthosis for gait assistance by B. G. Do Nascimento et al. [76]. The orthosis here presented consists of a pelvic braces and thigh supports, connected by a vertical articulated beam. A pneumatic artificial muscle is mounted in front of the orthosis on each leg, attached on the pelvic brace and on the thigh support. The actuator is contracted when the hip joint angle reaches a minimum extension value, and released when the joint angle reaches a preset flexion value.

A clinical study carried out with a patient having poliovirus reported that the patient was able to complete step transition in an improved manner, thanks to the effective performance of the controller.

Hip exoskeleton by C. Lewis et al. [77]. In this study, eight healthy subjects experimented the Michigan hip exoskeleton walking on a treadmill. This exoskeleton consists of pelvic part and thigh cuffs, which are connected with a joint allowing f/e, actuated by a pair of pneumatic muscles placed on the lateral side, and passive a/a. In the study, the hip exoskeleton provides hip flexion assistance from 33% to 53% of gait cycle, along a torque profile similar to the gait-data hip flexion torque. Each gait cycle starts from heel strike event, determined by a footswitch, and the gait period is averaged above the stride time of the previous ten cycles.

During the experimental sessions, participants walked with inactive exoskeleton for ten minutes, and active for thirty minutes. Results showed that the total hip torques (exoskeleton plus human muscles) were almost the same under the two conditions, despite the kinematic differences.

4.2. Knee Joint Exoskeletons

4.2.1. Model-based control

1 DOF exoskeleton by G. Aguirre-Ollinger et al. [78]. In this work, a control strategy based on an human-exoskeleton admittance model is proposed, combining the torque exerted by the exoskeleton with an inertia-compensating torque estimated from the angular acceleration. The reference trajectory produced by the model is tracked by a closed-loop controller consisting of a LQ regulator plus an integral term. Not basing on a compliant architecture, this system would impede the user natural motion: the purpose of the controller is to compensate for this drawback.

Subjects performed lower leg swing without exoskeleton, with exoskeleton, and with exoskeleton plus compensated inertia controller: results showed that the inertia compensation helped subjects to recover their natural swinging frequency and increase their own-selected swing angular velocity.

RoboKnee. This knee exoskeleton is designed to assist the wearer during stairs ascent and squatting with heavy loads [79]. RoboKnee consists of a thigh and a shank brace, jointed on the knee and connected by a linear SEA joint. In [79] a control algorithm is presented: the actuated torque is a fraction of the propelling torque, obtained by multiplying the ground reaction force – estimated as the force compressing the linear SEA – with its knee axis moment arm – obtained from the knee brace joint position sensor and knowing the distances of the linear SEA attachment points on the exoskeleton. It is worth noting that this estimation relies on the assumption that the ground reaction force is purely vertical. This kind of control strategy aims to relief the quadriceps muscle: in the performance evaluation test a user performed one-legged deep squatting with a 60-kg backpack more times than he did without RoboKnee.

TUPLEE. This is a mono-lateral knee exoskeleton actuating the knee f/e through a linear actuator [80]. Its controller uses a simplified bio-mechanical model which calculates the current muscular torques based on the EMG signals. The requested torque is proportional to the estimated muscular torque through EMG signals. Since the controller directly depends on the EMG activity, TUPLEE is suited for healthy people, or subjects with residual voluntary muscular control.

Experiments have been performed with a single subject, performing general daily-life activities movements, e.g. standing up, walking, climbing stairs, etc. TUPLEE could provide substantial supports for the user, the orthosis torque being consistent with the user's EMG activity.

Robotic knee exoskeleton prototype by A. Gams et al. [81]. This prototype of bilateral knee exoskeleton mechanism is intended for wearer's squatting motions augmentation. In their work, effects on the metabolic consumption of three different controllers are compared, including gravity compensation, position control and oscillator-based control. With the gravity compensation controller, the desired torque is calculated through a simplified knee joint model: a zero reference value when the knee is fully extended, and a positive extension force whenever the knee is flexed. As for the position controller, it follows a predefined desired position with the output torque linearly depending on the difference between current joint angle and the tracked joint position. In the oscillator-based control, an adaptive frequency oscillator synchronizes with the knee joint angles during squatting, with the desired torque calculated on the basis of a simplified joint model (which is also why we put it in the model-based control section).

Seven healthy young subjects performed five-minute squatting exercises under different control approaches, in a randomized order. During the tests, their oxygen consumption, minute ventilation, heart rate, blood oxygenation, and muscle EMG were monitored. The metabolic cost decreased with all the three methods in comparison with free squatting, with the oscillator-based controller showing the best energy-expenditure performances among the three controllers.

4.2.2. Predefined gait trajectory control

Powered Knee Orthosis (PKO). The PKO, developed to help the elderly and patients with gait disorders to achieve a more regular walking pattern, is presented in [82]. Its controller relies on the following assumptions: from human biomechanical walking data, hip and knee show similar trajectories during the swing phase. Hence, in swing phase, the desired knee angle is computed based on the hip joint angle through a polynomial interpolation of clinical gait data, while during stance phase, the knee is locked. A foot switch is incorporated in order to detect the interested gait phases.

Available results from one subject walking on a treadmill wearing the PKO confirmed the feasibility of this control strategy.

Stance control knee ankle foot orthoses (SCKAFOs). . This SCKAFOs is presented in [83]. It addresses knee assistance for subject affected by poliomyelitis. By detecting the foot pressure of the sound leg, the orthosis is controlled with a predefined torque profile. During mid swing of the disabled leg, the orthosis starts to provide a flexion torque, and during the late swing, the orthosis starts to help the knee extension. When the knee joint is fully extended, a constant torque is applied by the orthosis; the torque value is increased to compensate the reaction force during heel strike.

A 54-year-old male polio subject tested the orthosis: the assisted knee pattern was close to a normal one, a result difficultly achievable by him with a standard passive orthosis.

4.2.3. Muscle stiffness control

Knee orthosis by K. Kim et al. [84]. In this work, an assistive strategy based on muscle stiffness has been tested on a pneumatic actuated knee orthosis, with two pneumatic artificial muscles simulating the functions of rectus and biceps femoris muscles. The user's knee extension intention is estimated by the vastus intermedius muscle stiffness, according to which value the pressure in the pneumatic muscle is controlled. The muscle stiffness force sensor (MSFS) is composed by a pressure sensor and jig to quantity the pressure changes.

Twenty participants performed sit-to-stand and squat motions, ten times each, using the powered orthosis. The experimental results showed that under assistance, lower limbs muscular activity was reduced both during sit-to-stand and squatting motions.

Knee orthosis by N. Karavas et al. [85]. This exoskeleton consists of two cuffs for thigh and shank, and a rotational actuation system. The exoskeleton aims to empower the user's knee by augmenting the robotic joint stiffness, on the basis of a knee joint musculoskeletal model considering the non-linear relationship between muscular activation and joint torque. From the EMG signals and the joint angle, the model estimates the user's torque and the stiffness trend index, which are used to determine the desired joint trajectory and stiffness. A healthy subject's standing up trials proved the effectiveness of this knee exoskeleton and its assistive strategy.

4.2.4. Predefined action based on gait pattern

Knee extension assist device (KEA). This orthotic knee extension assist device for stand-to-sit and sit-to-stand tasks is presented in [86]. The KEA assistance derives from a spring and a pneumatic actuator. During stand-to-sit, the user's weight compresses the spring. To achieve a smooth knee flexion and sitting-down motion, the pneumatic actuator provides a slight flexion-braking torque, insufficient to overcome the weight load. After the sitting-down procedure finishes, the actuator is disabled and the compressed spring mechanically locked. During sit-to-stand, the spring is unlocked and provides vertical propulsion by releasing the previously stored elastic energy, and the actuator is activated again providing the extra knee extension torque.

Two healthy male adults were recruited to test the device. The KEA was incorporated within a conventional commercial KAF orthosis. Participants performed stand-to-sit and sit-to-stand motions in both deactivated and activated condition. A seven-camera motion analysis system was used to capture the motions, and surface electrodes recorded the EMG activity. Results demonstrated that both subjects were able to stand up and sit down in a slower, but more controlled manner when KEA was supplying assistance. However, the subjects' EMG results were not consistent, with one decreasing while the other one increasing the EMG activities.

MIT knee exoskeleton. The MIT robotic knee is a quasi-passive device: its motor does not exert mechanical power directly on the knee joint, but assist a floating spring to store and release energy depending on the running gait cycle [87]. A passive spring is attached on the shank: when the spring is compressed, the actuator fixes the spring carriage plate position; when the knee starts to swing, the actuator moves the carriage, allowing the knee a free extension. In the available literature, only performances characterization on the bench are provided, without evaluation tests on a human user.

4.3. Ankle foot orthoses

4.3.1. Proportional myoelectrical control

AFO by P. Kao et al. [88]. This AFO, developed by University of Michigan, is mounted with two pneumatic artificial muscles actuating the ankle d/p. This AFO is built mainly for in-lab studies on the human ankle kinematics and response to external assistance, e.g. the joint torque patterns with the powered orthosis [88], the neurological response to the assistance [89]. In [88–90], the AFO has been used with a proportional myoelectrical controller. The desired pressure in the pneumatic actuators is proportional to the processed EMG signal of a selected muscle.

Experimental results showed that the muscle activities were decreased under the AFO assistance. Further analysis results suggested that the primary neurological reaction to the powered assistance was to keep the total ankle joint torque (human muscular torque plus AFO torque) invariant [88], as in general happens in response to external perturbations [89].

Powered Ankle-Foot Orthoses (PAFOs). In [91] a pair of powered ankle-foot orthoses, PAFOs, providing d/p assistance through pneumatic muscles emulating the behavior of the soleus muscle are presented: assistance is provided on the basis of a proportional myoelectrical control from the soleus EMG envelope.

Nine young and seven elderly adults completed experimental sessions investigating three walking conditions: standard shoes, inactive PAFOs and active PAFOs. The experimental sessions included a familiarization process, in which each subject chose his/her preferred walking speed. Results showed that both young and elder adults increased their self-selected walking speed when plantar flexion was assisted; for elderly adults, metabolic consumption of walking with assistance was lower than other two walking conditions, while for young adults, the metabolic consumption under assistive mode was lower than the no-assistance condition, but still higher than free walking mode.

4.3.2. Model-based control

IPEC AFO. In [92] a prototype of an active ankle-foot orthosis, IPEC, integrating a SEA with a standard passive AFO is presented. The assistance mainly derives from a pretensioned spring, connected to an actuated linear slider through a moment-arm leverage. A kinematic model for the IPEC AFO is used to predict the applied torque, basically equal to the spring force multiplied by leverage-reduced position of the slider.

Only bench tests were performed, demonstrating that the IPEC could provide assistance for ankle plantar flexion.

Stewart-platform-type AFO by H. Takemura et al. [93]. A wearable Stewart-platform-type ankle-foot orthosis has been proposed as a wearable and portable rehabilitation tool and a walking assistive device. This assistive device has six linear pneumatic actuators mounted between the leg plate and the foot plate, two behind the heel and two at each side of the foot. The ankle position and the torque control of the pneumatic cylinders are based on a classic forward/inverse robot kinematic model.

The posture measurement performance and motion reproduction performance were proved with five subjects wearing the device and rotating their ankle randomly, but no additional clinical test was presented.

4.3.3. Muscle stiffness control

Ankle orthosis by K. Kim [94]. This AFO is designed for assisting ankle plantar flexion of elderly subjects; it is composed by a basic single DOF exoskeleton and an artificial pneumatic actuator. In their work, the soleus muscle stiffness is measured with MSFS and used to control the pneumatic muscles' air pressure.

Fifteen young adults and fifteen elderly people were selected for validation experiments, executing plantar flexion without the orthosis, with the orthosis but without assistance, and with assistance. EMG signals of lower-limb muscles and ankle plantar flexion torque were measured and analyzed: the results from all the subjects showed a general decrease of the muscular torque peak value.

4.3.4. Predefined action based on gait pattern

MIT active ankle-foot orthosis (AAFO). The MIT AAFO has been designed to assist ankle movement of patients having drop-foot gait [95]. It is composed by a standard polypropylene AFO mounted with a SEA joint. During the early stance, the intrinsic stiffness of the SEA linear torsional spring prevents foot slap; in the late stance phase, the joint is controlled as to minimize its impedance (zero-torque modality, continuously tracking a zero deformation of the SEA spring), in order not to hinder the user's ankle plantar flexion; during the swing phase, the actuator assists lifting the foot from ground to avoid drop foot.

Clinical trials were carried out with two patients suffering from drop-foot. Gait data analysis proved that the AAFO could reduce the occurrence of drop foot and help the patients to execute a more natural gait.

AFO by P. Malcolm et al. [96, 97]. In these works a bang-bang control was applied to an AFO, structurally similar to the one developed in University of Michigan, for studying the effects of an active AFO in human locomotion. The pneumatic muscle is activated at different percentage of the stride cycle, and is switched off in correspondence of the toe off moment [97].

Ten subjects walked with this AFO on a treadmill, undergoing metabolic consumption measurements and gait pattern analysis. It was found that the assistance was more helpful when the pneumatic muscle was activated just before the heel strike of the contra-lateral foot.

5. Conclusion

The following Table 2 collects and exposes the previously presented results: two main panels are provided, one for the multi-joint and one for the single-joint systems. Both panels are divided among the employed assistive strategies (columns): in the first panel, rows divide the multi-joint exoskeletons according to the main assistive purposes; while in the second panel, rows separate the addressed single-joint (hip, knee or ankle) exoskeletons. In each cell, validations carried out with the exoskeletons are briefly reported.

In this paper, we have reviewed various kinds of assistive strategies employed in powered lower-limb exoskeletons for the selected literature, including both multi-joint and single-joint devices and focusing on the systems with user-in-the-loop validations. Generally, an assistive strategy has to deal with two main issues regarding the user-exoskeleton mutual interaction: a physical interaction, i.e. the mechanical power transfer, and a cognitive interaction, for information exchange [98]. These two issues are reciprocally affected. A consistent and effective mechanical power transfer is fundamental for the wearer comfort, and for the exoskeleton to rely on correct kinematics and kinetics information; vice versa, when and how to deliver a mechanical assistance to the user depend on the user's motion intention. While the physical interaction is mostly related to the low level controller – e.g. bandwidth of the system, motor own dynamics, performances and characteristics of the power supply and of the actuation elements (leverages, springs, pneumatic chambers), the kind of controller (position, velocity or torque control) –, the cognitive interaction depends on the high level controller, i.e. the global assistive strategy, which we aimed to explore and compile in this paper.

5.1. Motion intention detection

The methodology to detect motion intention varies according to the different targeted motion tasks and typology of users. The exoskeletons reported in this paper have been designed to assist different kinds of human lower-limb movements, such as supporting heavy loads, level walking, sit/stand transitions, squatting, ascending and descending stairs, and even running. The targeted subjects are also diversified, including elderly people, healthy people, people with muscular weakness, people with lower-limb disability or totally lose lower-limb functions.

Though the kinematics and kinetics characteristics of lower-limb joints greatly differ in each kind of motion, in the control process they are usually divided into a series of phases: detection and prediction of these phases are based on the exoskeleton sensory systems, which are fundamental for the control strategy. For example, level walking could be segmented into stance and swing phases, which can be straightly detected with simple foot pressure sensors; climbing stairs intention detection could be completed by shifting body weight and moving leg, which are more easily recognized through joint angle sensors, accelerometers, and ground reaction force sensors. Moreover, when the users have (completely, or residual) lower-limb muscular activities, their motion intention could be detected directly

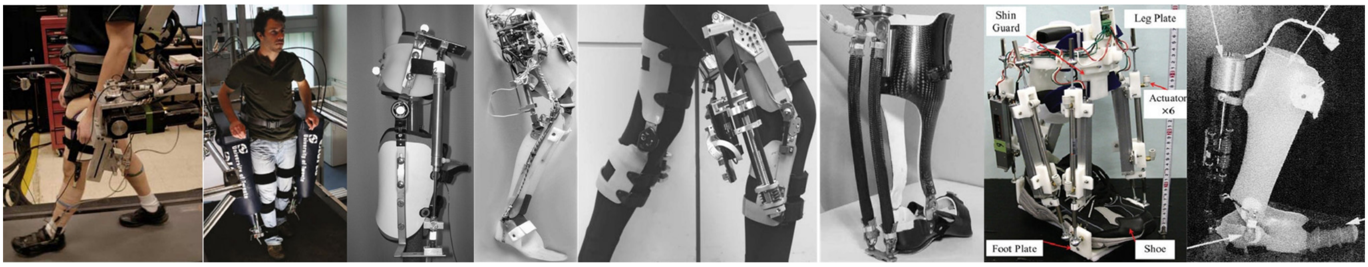

Figure 4: ALEX II [73], LOPES [55], Hip exoskeleton by C. Lewis et al. [77], TUPLEE [80], MIT knee exsokeleton [87], Ankle-foot orthosis (AFO) by P. Kao et al. [88], Stewart-platform-type AFO by H. Takemura et al. [93], MIT AAFO [95].

by measuring EMG and/or muscle stiffness. However, the muscular activities change between tasks and subjects, and even for the same subject executing given tasks at different time: hence, a repeated calibration and a not-negligible signal processing are required. When a real-time application is implemented, the time-dependence of the muscular signals during the operation could also bring inaccuracy for the whole control system.

5.2. Assistive strategy with targeted tasks

Based on the variety of walking-related signals, and aiming at assisting various tasks and types of users, several assistive strategies have been proposed and adopted in recent exoskeletons. As shown in Table 2, assistive strategies in multi-joint and single-joint devices partly overlap.

For paraplegic or people with severe lower-limb disability, a predefined trajectory control is mostly used. The trajectory is recorded from a healthy person, or extracted from clinical gait analysis data, and then replayed. To improve the flexibility and the comfort, more recent studies suggest to parameterize the joints trajectories in accordance with the users body conditions and movement phases. Paraplegic patients usually have special requirements for maintaining balance, as they experience difficulties in standing still without external support. In the literature, most of the assistive strategies aim to provide assistance in the sagittal plane, which is the one with higher dynamic and energy exchanges between the limb segments and the ground [99], but this is not sufficient to provide stability support. Only very few assistive strategies focused on the stability issue by addressing the hip a/a movements.

A model-based assistive strategy is also frequently used for both healthy and lower-limb disabled subjects, or for loading capability augmentation. Despite being straightforward and widely applicable, its efficacy depends on the accuracy of the human-exoskeleton model which is always complicated due to the multi-body interaction dynamics.

With the introduction of an adaptive oscillators-based controller, it is possible to realize a model-free control able to synchronize with joint angles, or other periodic bio-signals, and to provide a continuous gait phase. Then the requested assistance is calculated by implementing a gait phase based torque envelope. Oscillators only synchronize with (quasi-) periodic signals. So this kind of assistive strategy is suitable for people who can generate periodic gait signals, such as healthy people or persons with residual motion capability: it is not necessary, however, that their gait pattern is symmetrical among left/right leg.

Fuzzy controller is an attempt to build neurologically inspired bio-mechanical models, which can return the desired movements by merging different bio-mechanical signals. But, as the cited literature has presented, there are numbers of parameters that need to be configured, so this controller is time consuming and computation costing.

A peculiar class of exoskeletons is built without a rigid structural frame, but wearing the user with belts, straps, air bags: the most relevant examples in this review are the Soft Exosuit [67] from Harvard University and the Power Assist Wear from Okayama University [66]. The actuators activation in this case is controlled based on gait phases: only healthy or lowly muscle weakned subjects can benefit from these devices. Some pneumatic activated exoskeletons, like the AFO by University of Michigan [88], and quasi-passive devices, like the MIT exoskeleton [11], also have adopted this gait event-related control principle.

For load-carrying capability augmentation purpose, sensitivity amplification control is quite effective, based on which the BLEEX successfully proves its functionality, helping a subject to walk while carrying heavy loads.

There are also some devices hybridizing different strategies in different gait phases: while this could improve the accuracy of specific pattern, the switch between each strategy could bring non-trivial discontinuity in the control.

5.3. Validations with human in the loop

Among the reviewed literature, each research team has validated the proposed assistive strategy and the related exoskeletons in different manners. The most addressed evaluation indexes are the EMG activities: the aim is to prove that lower-limb muscles could directly benefit from assistance. Assistive exoskeleton effectiveness has also been addressed by measuring the metabolic consumption of their wearers, or other biometric parameters (e.g. heart rate) representing their whole body status during performing a task. Cognitive validation is of importance as well, since it is expected that a symbiotic and usable exoskeleton does not hinder, or could remain compliant to, the user's intended movements. Due to the complexity in evaluating user's psychological effort, in the reported studies, there are only few works involving these indexes, but still in a quite simple way, e.g. examining the patients to keep eye contacting

CONTROL STRATEGY:	Sensitivity amplification	Predefined gait trajectory control	Model-based control	Adaptive oscillators-based control	Fuzzy control	Predefined action based on gait pattern	Hybrid assistive strategy
Load carrying augment-ation	**BLEEX [24-26]:** walking at 1.3 m/s with 34 kg payload. **NAEIES [27]**: neural network. Only simulations with a reduced number of DOFs.		**BE [44-45]**: full-body exoskeleton. Only simulations tests. **Nurse Robot Suit [46-47]**: subject holding a 60 kg payload.			**MIT exoskeleton [11, 68]**: relieving 90% of the payload to the ground, but increased metabolic consumptions.	**BLEEX [69]**: subject walking, 0.5 m/s with 18 kg payload, holding an handrail. Worse than sensitivity amplification.
Healthy subject assistance				**Tagliamonte et al. [57]**: healthy subject walking comfortably on a treadmill. **Zhang et al. [59-60]**: increased step length and speed, reduced efforts.		**Sasaki et al. [66]**: reduced EMG in stair ascent. **Soft Exosuit [67]**: providing 18% of human torques.	
Elderly, muscle weak, partially impaired subjects		**Ikehara et al. [35-36]**: healthy subject decreased EMG values. Impaired patient received only knee assistance: +7.4% range of motion.	**WWH [48-49]**: subject performing sit-to-stand & climbing with reduced EMG and heart rate. **WPAL [50]**: bench test validating system compliance to user motion. **XoR [51-52]**: test with dummies.	**Matsubara et al. [58]**: simulations proving feasibility and stability of the controller.	**He et al. [63]**: healthy subject, sit-stand transitions and squatting with reduced EMG. **EXPOS [64]**: elderly subject, sit-stand transition, -32% muscular effort.		**Yeh et al. [70]**: healthy subject reducing EMG from -20% till -36%, in walking-climbing-descending.
Quadri-plegic, paraplegic, completely disabled patients (SCI)		**ATLAS [6, 28]**: quadriplegic children walking. **HAL [12, 29]**: kinematic analysis showing feasibility. **IHMC [30] and Mina [32]**: healthy subjects walking passively. SCI walking at 0.2 m/s, no cognitive effort. **MINDWALKER [33-34]**: SCI decreasing EMG in lower limb, increasing in arm (forearm crutches support). **ReWalk™ [7, 37]**: 5-10' walking for 50m at 0.45 m/s. **eLEGs [8]**: SCI performing sit-stand transitions. **Vanderbilt [38-40]**: paraplegic walking and climbing stairs, with handrail supports.	**HAL [41-42]**: reducing muscular effort in knee. Impaired subject performing sit-stand transitions holding an horizontal bar. **ABLE [43]**: a subject with no residual leg mobility performed standing-up, gate passage and straight level walking.			**Belforte et al. [65]**: both healthy and paraplegic subjects could walk, but not adaptive orthosis and not smooth signals.	**AIT leg exoskeleton-I [71]**: a validation on a bench with a simplified human body model.

CONTROL STRATEGY:	Predefined gait trajectory control	Model-based control	Adaptive oscillators-based control	Predefined action based on gait pattern	Muscle stiffness control	Proportional myoelectrical control
Hip		**Yu et al. [75]**: simulation and validation of the un-worn system.	**ALEX II [23, 73]**: healthy subjects reduced EMG envelope. **LOPES [5, 55]**: healthy subjects reduced energy consumption. **Aguirre-Ollinger [74]**: time coordination of the powered torque and the EMG activities.	**Do Nascimento et al. [76]**: polio subject improving step-to-step. **Lewis et al. [77]**: subjects replacing their muscular torques with the exoskeleton ones.		
Knee	**PKO [82]**: subject walking on a treadmill, confirming feasibility of the strategy. **SCKAFOs [83]**: an elderly polio subject walking with a resorted normal knee pattern.	**G. Aguirre-Ollinger et al. [78]**: subjects swinging legs at their natural frequency. **RoboKnee [79]**: reduced fatigue while squatting. **TUPLEE [80]**: supporting a healthy subjects in ADLs. **A. Gams et al. [81]**: healthy subjects performing squat with reduced metabolic cost.		**KEA [86]**: stand-sit transitions. Not consistent EMG data. **MIT knee exosk. [87]**: only test bench characterization.	**Kim et al. [84]**: subjects reducing EMG activities in sit-stand transitions and squats. **Karavas et al. [85]**: subject testing standing-up task.	
Ankle		**IPEC AFO [92]**: only bench test. **Takemura et al. [93]**: evaluation of users free-motion capabilities.		**MIT AAFO [95]**: reduced slap-foot occurrence. **Malcolm et al. [96-97]**: assistance in ankle thrust for healthy subjects on a treadmill.	**Kim [94]**: subj. walked with EMG evaluation.	**Kao et al. [88-90]**: decreased muscular activity (healthy). **PAFOs [91]**: elderly subjects reduced metabolic cost.

Table 2: Conclusion of assistive strategies applied by multi-joint exoskeletons and single-joint exoskeletons.

during experiments. Similarly, due to the current prototypical nature of human augmentation/assistance devices, also safety and dependability factors (fail-safety, risk analysis of a given assistive strategy, switching to an ‘emergency’ operation mode and even its definition) have been poorly explored: most tests and researches involving human subjects using lower-limb exoskeletons have tried to evaluate – in a more quantitatively possible manner – the effectiveness of a given assistive strategy, or how to tune it in order to maximize a certain performance index.

5.4. Future expectations

With the development of assistive technology, exoskeletons will play an increasing important role in our daily life, especially for people with continuous needs in locomotion assisting, but desiring a level of autonomy. An assistive exoskeleton is able to provide assistance in different motion tasks: walking, running, sit-to-stand/stand-to-sit, ascending/descending stairs, lifting heavy loads. In the literature, the assistive strategies for these different tasks are mostly validated separately. Very few validations including two or more continuous tasks have been presented so far, and at the current level they underlie on state machines and vocal commands which do not easy switching between tasks, thus interrupting the user's movements. Finally, for an exoskeleton aiming to provide daily-life movement assistance, how to ensure a safe cooperation with human on the assistive strategy level is also an issue worth to be challenged, but has not yet attracted much attention in the literature.

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