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Review of assistive strategies in powered lower-limb orthoses and exoskeletons

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HIGHLIGHTS

- We collected lower-limb orthosis/exoskeleton papers from Web of Science and Scopus.
- We classified the collected papers according to the adopted assistive strategies.
- We reviewed each orthosis/exoskeleton focusing on their control strategy.
- We also provided the relevant validations of each assistive strategy.

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ABSTRACT

Starting from the early research in the 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 with a focus on the way they are controlled to deliver assistance; the relevant validations are as well investigated, 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.

1. Introduction

The initial studies about lower-limb orthoses for motion assistance can date back to the 1960s in the United States [1] and in the former Yugoslavia [2], respectively for military and medical service 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 – LokoMat [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 systems empowering healthy people 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 aging 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

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and high life expectancy in these countries, the aging 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 acknowledgment of these devices. In 2008, A.M. Dollar and H. 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, they 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 our research topic 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 [23]: the robot provides mechanical power and feedbacks information to the human, and receives the intended movement information 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*.

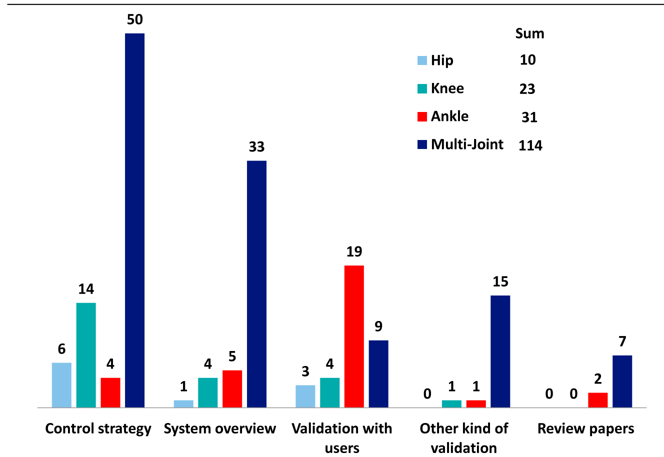
In particular, in this review paper we will address assistive strategies of lower-limb exoskeletons utilized to supply additional energy for daily-life movements of healthy young and elderly people and those suffering from lower-limb muscular weakness or disabilities. Reported studies will be categorized 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 [24] – will not be included directly, since the rehabilitation treatment of these systems aims to override the user's volitional movements and 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 classify the collected papers into several categories. Then, we present the reviewed assistive strategies in accordance with the involved 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:

Table 1
Different categories of papers collected for the review.



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 improve* OR augment* OR enhance* OR climb stairs OR reinforce*) 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 remained 178 all written in English and published in journals or conference proceedings after 1990.

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 a human wearing the exoskeletons. Analyzing these papers is necessary to evaluate how the assistive strategy effects on users.