Medical Engineering & Physics 34 (2012) 397–408

Contents lists available at SciVerse ScienceDirect

Medical Engineering & Physics

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

Review

Review of control algorithms for robotic ankle systems in lower-limb orthoses, prostheses, and exoskeletons[☆]

R. Jiménez-Fabián, O. Verlinden[*]

Service de Mécanique Rationnelle, Dynamique et Vibrations, Faculté Polytechnique, Université de Mons, Belgium

ARTICLE INFO

Article history:
Received 10 December 2010
Received in revised form
18 November 2011
Accepted 20 November 2011

Keywords:
Robotic ankle systems
Active and semiactive orthoses/prostheses
Exoskeletons
Control algorithms

ABSTRACT

This review focuses on control strategies for robotic ankle systems in active and semiactive lower-limb orthoses, prostheses, and exoskeletons. Special attention is paid to algorithms for gait phase identification, adaptation to different walking conditions, and motion intention recognition. The relevant aspects of hardware configuration and hardware-level controllers are discussed as well. Control algorithms proposed for other actuated lower-limb joints (knee and/or hip), with potential applicability to the development of ankle devices, are also included.

Contents

[☆] Developed under the project Biofact FEDER No. 2029.

[*] Corresponding author at: Boulevard Dolez 31, BE-7000 Mons, Belgium. Tel.: +32 065 37 4284; fax: +32 065 37 4183.
E-mail addresses: rene.jimenez@umons.ac.be (R. Jiménez-Fabián), olivier.verlinden@umons.ac.be (O. Verlinden).

1350-4533/$ – see front matter © 2011 IPEM. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.medengphy.2011.11.018

1. Introduction

The ankle–foot complex plays an important role in human locomotion. The stance phase of walking involves an intricate dynamical behavior of the lower limbs and its interaction with the floor. The ankle flexor and extensor muscles are crucial to provide vertical support and forward progression of the body [1]. The lack of the ankle functionality represents a very important limitation for walking and many other human activities.

For low-speed walking, the commercial passive orthoses and prostheses can mimic the behavior of a healthy ankle in a satisfactory way. However, for normal and fast walking speeds, the ankle provides additional energy for propulsion at the plantar flexion phase [2,3]. The lack of a source of energy in passive orthoses and prostheses is commonly associated to gait deficiencies and a higher metabolic energy consumption.

During the last five decades, researchers have been developing active and semiactive ankle devices to help impaired individuals to walk in a more natural way. Many important results have already been achieved. However, there are several factors that limit the general use and commercialization of these devices. Portable power supplies, lightweight actuators, and high-efficiency transmissions are some of the most important issues that still need improvement [4]. In the case of active orthoses, the specific nature of the ankle disabilities, that widely varies among patients, makes very difficult the development of general design methodologies. In particular, the development of general control strategies is challenging.

Active ankle devices can be classified in three categories: (1) prostheses and orthoses, (2) rehabilitation robots, and (3) powered exoskeletons. A thorough review on the past and current research on exoskeletons and active orthoses is presented in [4] and also in [5], where a general framework for the study and classification of these devices can be found. Versluys et al. [6] give an overview of the evolution of the prosthetic feet, going from completely passive models to active prototypes. Marchal-Crespo and Reinkensmeyer [7] present a review of supervisory strategies for rehabilitation robots, emphasizing the aspects that induce plasticity on the patients.

From the mechatronics perspective, exoskeletons, active orthoses/prostheses, and rehabilitation robots are very similar at the functional level. However, control objectives and human interfaces are essentially different for each device category.

Active orthoses and prostheses might involve user motion intent recognition and adaptation to different working conditions (e.g., different walking speeds and walking surfaces, in the case of a lower-limb device).

The main difference between prostheses and orthoses resides in the hardware configuration. Orthoses are worn on the existing but impaired limb. Thus the control system has to deal with a possible lack of coordination between the user and the orthosis (involuntary muscle reaction) and with the intrinsic limb dynamics. Besides, the hardware weight is added to the limb weight. One of the main problems still encountered in the design of active orthoses is the weight of the components (specially the actuator) which constitutes an important limitation for the development of autonomous and efficient devices.

Prostheses replace lost limbs and, in the case of lower limb devices, the total weight in some recent prototypes is close to that of the replaced limb.

The primary objective in control schemes for rehabilitation devices is the reproduction of motion sequences to facilitate the patient's recovery. Trajectory-tracking controllers are commonly employed in these systems to impose repetitive motion patterns (see, for example [8]).

The control objective of an exoskeleton is to follow the movements of a healthy user, augmenting his/her physical capabilities for specific tasks in a relatively safe and transparent way. Although orthoses and exoskeletons share many functionalities, the term orthosis usually designates an assistive device for a patient with a motor pathology [5]. The large variety of ankle robots that has been proposed to date is also accompanied by a large variety of control strategies. Nevertheless, some features are common to many control schemes as, for example, the use of finite-state machines for gait phase detection. At the hardware level, the mechanical components and sensors used in the prototypes usually confine the nature of the low-level controllers to particular configurations.

The generation of control signals for active prostheses and orthoses can be addressed using different sources of information. The main categories are: (1) biomechanical signals, (2) electromyographic (EMG) signals, (3) peripheral nervous system signals, and (4) central nervous system signals [9]. However, mechanical and, in a less extent, EMG interfaces predominate in the reviewed works.

The level and rate of human adaptation to the use of active devices are strongly related to the user interface and to the control method. Cain et al. [10] compared the level of user's adaptation to an active orthosis using a foot-switch "bang-bang" controller and a proportional EMG-based controller. According to their results, the nervous system can adapt more easily to the continuous response of the proportional control than to the discontinuous response of the foot-switch control.

The present work reviews recent control strategies proposed for active and semiactive ankle devices. Special attention is paid to the algorithms for motion intention recognition, adaptation to different walking conditions, gait phase identification, and generation of walking patterns. Control algorithms for knee and hip devices are also included to extend the panorama of ideas that can be applied to control ankle devices. When available, experimental and numerical results are mentioned to illustrate the behavior of the algorithms.

In the following sections, the term control system is used to denote the assemblage of control elements (hardware and software). The term control scheme refers to the set of control algorithms in all levels of the control hierarchy. The term controller is used to designate the physical implementation of a dedicated algorithm, usually in charge of a particular task. For instance, gait events are used as inputs to finite-state controllers that switch between different low-level controllers for the actuators.

The manuscript is arranged as follows: Section 2 gives a short description of human gait to introduce the basic elements of ankle biomechanics. Section 3 presents algorithms based on gait pattern generators. Algorithms that implement different control strategies according to the gait events are discussed in Section 4. More sophisticated algorithms that try to determine the user's motion intent are presented in Section 5. Section 6 provides a description of some algorithms whose general structure do not fit in the previous categories. Final remarks are given in Section 7. A summary of the key features of the control schemes and their hierarchical structure is presented in Table 1.

2. Human ankle biomechanics

For the discussion of the different control algorithms it is convenient to have in mind the main aspects of human locomotion. This brief review of the ankle biomechanics will be restricted to the case of ground-level walking, as most of the proposed algorithms are related to it.

The ankle motion during ground-level walking is quasi-periodic and is usually divided into two main phases: the stance phase and the swing phase. The ideal gait cycle is typically defined as starting with the heel strike of one foot and ending at the next heel strike of the same foot. The stance phase begins when the heel strikes the