Gait parameter adaptation for lower-limb exoskeletons

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Abstract. The field of exoskeletons and assistive orthotic devices is a multidisciplinary issue in the halfway between medicine and robotics. Within the robotic discipline, bipedal robot gaits are generated as a function of parameters such as stride length, foot clearance and body height. These features allow to adapt the gait to different surface characteristics. However, biped robot gaits do not look as natural as human gaits. On the other side, gaits imposed in actual active orthoses are fixed following the Clinical Gait Analysis (CGA) pattern. These CGA patterns ensure a comfortable, natural and safe gait, but do not exhibit flexibility to change some gait features to adapt to the characteristics of the terrain, such as slopes or small obstacles. This paper presents the development of an adaptable gait pattern for a full lower limb active orthosis. Based on an impedance control approach, gait parameters such as step height, body height or step length are modified online, providing a safe and smooth gait pattern. Two shoe insole pressure measurement systems provide ground reaction force and center of pressure to adapt these gait parameters online. To avoid abrupt movements that would affect user comfort, references on position and speed must be smooth, that is, derivable when the characteristics of the gait change. To ensure that position and speed references follow a derivable path, with a very low computational cost, the change from one reference path to another has been modulated with Gaussian windows. Thus, a more adaptable orthosis with soft motion is achieved.

Keywords: Powered active orthosis, Gait trajectory generation, Exoskeleton, Gait parameter adaptation.

1 Introduction

Exoskeletons for human lower-limbs are robotics devices worn by an operator that fit closely and operate in parallel with the human legs, augmenting human performance. In the field of exoskeleton devices a classification can be made depending on the disease and potential for improvement of the user abilities:

- *Rehabilitation exoskeletons.* In a case of patients with neurological injury or with chronic incomplete spinal cord injury (SCI), a gait rehabilitation exoskeleton can help the user to relearn and recover the motion of their limbs. These rehabilitation exoskeletons [1] reproduce the motion of the user limbs in a body-weight supported treadmill [2]. This motion helps in the formation of user new neural path-ways to relearn to walk [3].
- *Exoskeletons for partial assistance.* In the case that user has lost strength in some of his or her limbs, such as an aged user, this portable exoskeleton device can detect the user intention by the use of electro-miographical signal (EMG) and augment it [4], like in the hybrid assistive limb (HAL) [5, 6].
- *Exoskeletons for full support assistance.* If the patient suffers from a complete spinal cord injury (SCI) which has resulted in paraplegia or quadriplegia, an assistive exoskeleton that helps to walk a person with lower-limb pathology can replace the function of a wheelchair. These types of exoskeletons are called active or powered orthoses. An active orthosis besides offering much more mobility than a wheelchair, significantly improves the circulation, bone density and excretory system of user. These devices are worn around the legs and back of the user to provide locomotion.

Nowadays, some commercial active orthoses like ReWalk from Argo Medical Tecnologies (`http://www.argomedtec.com`) or eLegs from Ekso Bionics (`http://www.eksobionics.com`) and some research devices like Mina [7] or Vanderbilt [8] use position control mode with a fixed angle pattern, obtained from clinical gait analysis (CGA), for each joint to walk. This angle pattern ensure a comfortable and natural gait, but it is fix and it does not adapt to characteristics of the terrain. In this paper we present the ATLAS orthosis which represents the next step in lower-limb active orthosis, because it can adapt the gait parameters while walking, achieving a smooth and more natural gait. Mechanical design and sensorial system of ATLAS orthosis are described in Section 2. The compliance adaptive controller implemented is presented in Section 3. The generation of the gait patter to achieve smooth trajectories is analyzed is Section 4. Finally Section 5 presents the main conclusions.

2 ATLAS orthosis concept and design

In orthotic terminology ATLAS orthosis (see Fig. 1) can be considered as an active THKAFO (Trunk-Hip-Knee-Ankle-Foot Orthosis). ATLAS is intended to support a 25-kg girl affected by quadriplegia and help her to walk at a moderate speed ($\leq 1m/s$). In the first stage of our project we use a walking frame to ensure stability. It is a 6 degree of freedom (DOF) mechanism, having 3 DOF per leg; hip, knee and ankle to allow the user to move in the sagittal plane. This first prototype features two actuated DOF per leg at hip and knee and a passive ankle. The flexion and extension motion of the hip and knee joints is driven by electrical brushless Maxon motors in combination with harmonic drive units. The setup provides repeated peak torque up to 57 Nm, and average torque of 32 Nm at speed higher than 20 rpm for each actuated joint. At the ankle,

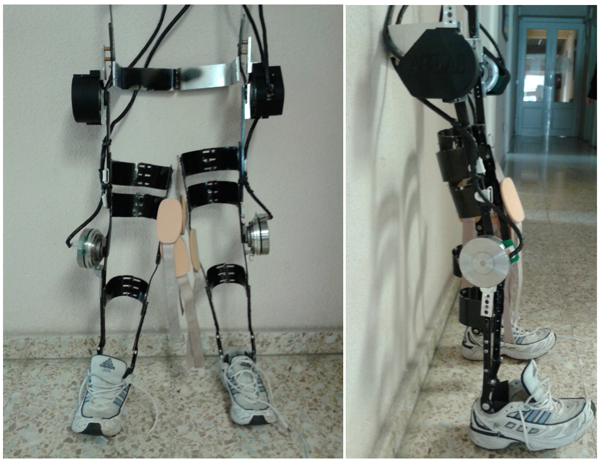


Fig. 1. Front and lateral view of ATLAS exoskeleton.

a steel cable has been attached, acting like a synergic biarticular linkage and transferring motion from hip and knee joints. Details of this novel configuration can be found [9]. In this way, we prevent high inertia in the more distal limbs. The orthosis is adjustable for height, allowing a range of user heights from 140 cm to 165 cm and a maximum weight of 50 kg. The sensorial system is composed of goniometers at hip, knee and ankle to measure user joint angles and an in-shoe plantar pressure measurement system at each foot (see Fig. 2) that provides the total ground reaction force (GRF) and the center of pressure (COP). This insoles are based on a matrix of 85 conductive pressure sensors distributed along the sole area measuring a pressure range of 15-600 kPa with a resolution of 2.5 kPa. This amount of sensors allow very precise location of the center of pressure. This amount of sensors allow very precise location of the center of pressure and a correct measurement of the ground reaction force.

3 Compliance controller

The control of an active orthosis for quadriplegic users has to be thought of in a similar way as an autonomous biped robot. Therefore we have implemented a control scheme based on a compliance controller, adapted from [10], which basically uses parameterized joint trajectories as equilibrium points while small forces are allowed to separate slightly from those equilibrium points in order to allow for some compliance. The control scheme is shown in Fig. 3. The desired foot forces are calculated to support the user weight and maintain the center of pressure within the desired path. Actual cartesian force vector is calculated from the values obtained with the insoles. Therefore, the active compliance equation for each leg has the form:

$$\mathbf{F_{des}} - \mathbf{F} = -\mathbf{K_p}(\mathbf{X_{des}} - \mathbf{X})\mathbf{K_f}^{-1} + \mathbf{X^{ref}}\mathbf{K_f}^{-1} \tag{1}$$

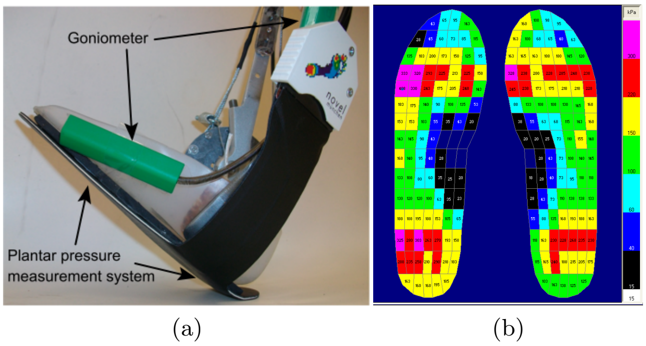


Fig. 2. Goniometer and flexible in-shoe plantar pressure measurement system: (a) Insole and 2D goniometer attached; (b) Pressure analysis

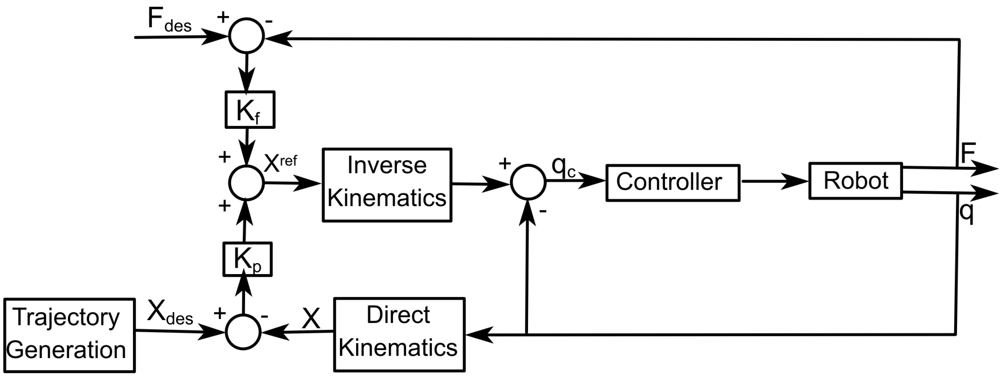


Fig. 3. Block diagram of the active-compliance controller

where $\mathbf{X}$ is the vector of actual cartesian position of the foot, $\mathbf{X_{des}}$ is the vector of reference positions obtained from parameterized trajectories, $\mathbf{F}$ is actual force sensed from insoles in stance and $\mathbf{F_{des}}$ is the vector of desired Cartesian foot forces, obtained from the force-distribution algorithm [11]. $\mathbf{K_p}$ and $\mathbf{K_f}$ are diagonal matrices of gains. $\mathbf{X^{ref}}$ are cartesian foot position references as inputs to joint controllers after inverse kinematics transform.

These final position reference, $\mathbf{X^{ref}}$ and its derivative are traced by the controller through a PD current control scheme.

$$\mathbf{I} = \mathbf{K_{ip}}(\mathbf{X} - \mathbf{X^{ref}}) + \mathbf{K_{id}}(\dot{\mathbf{X}} - \dot{\mathbf{X}}^{\mathbf{ref}}) \tag{2}$$

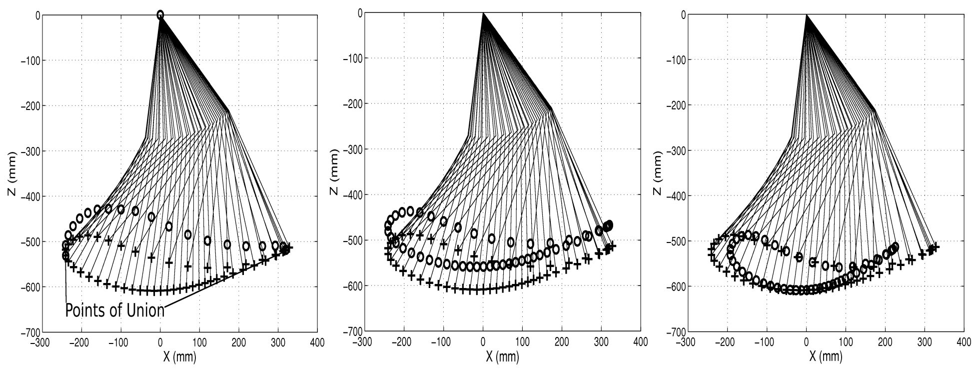
where $\mathbf{X}$ is again the actual position, $\dot{\mathbf{X}}$ is the actual velocity and $\mathbf{I}$ is the current vector.

4 Gait pattern generation

Traditional orthoses base their movement on the tracking of clinical gait analyses (CGAs) patterns, which are de-normalized and adjusted to the user. This gait trajectory ensures an ergonomic and natural gait. However, they cannot adapt to the environment characteristics. Biped robots, on the other side, use adaptable gaits. To go further, the gait parameters in an active orthosis should be modifiable like biped robots do.

ATLAS project uses CGA based gait trajectories. However, the parameters of the gait are changed as a function of the ground reaction force and the centre of pressure sensed by the insoles. ATLAS orthosis can modify the ground clearance, the body height and the step length. Fig. 4 shows how the foot trajectory changes when these parameters change. These new reference trajectories have to be defined without abrupt movement, this is, the final path that the foot must follow must be differentiable.

Let examine more deeply how the references are modified when ground clearance increases, this will give an idea of how to get differentiable reference in all the other cases. To achieve the original CGA motion in the foot the angle and angular speed references at the knee are those shown in Fig. 5. Both angle and angular speed references are differentiable. If the reference path is changed to one with more ground clearance (see Fig. 4 (a)), the angular speed reference is not differentiable. Fig. 7 (a) shows abrupt speed changes. As a result of requiring more ground clearance, only the swing is changed and swing and stance trajectories merge with different slope at the point of union.



(a) (b) (c)

Fig. 4. Original foot path obtained by CGA *(marker +)* and modified *(marker o)* to (a) provide more ground clearance (b) reduce body height (c) reduce step length.

To avoid these type discontinuities, which would produce a tremor in the limb, we propose to modulate the transitions between two trajectories by a

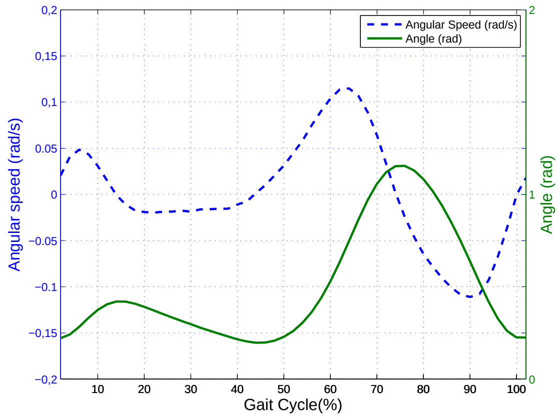


Fig. 5. Angles and speeds in the knee for the original CGA path.

unitary Gaussian function:

$$F_{\mu,\sigma}(X_{des}) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(X_{des}-\mu)^2}{2\sigma^2}}, \tag{3}$$

where μ is the mean and σ is the standard deviation of the Gaussian function. It has been chosen $\mu = 0$ for centering Gaussian curve correctly and $\sigma = \frac{1}{\sqrt{2\pi}}$ so that the amplitude of the Gaussian is unitary and thus achieve adequate bonding of the curves. Figure 6 shows the Gaussian window used. These windows are usually used in the communication filtered processes. Figure 7 (b) shows the knee references when the trajectories are joined modulated by a unitary Gaussian window, differentiable references are obtain. There by, a smoother trajectory is obtained which is more comfortable for the user.

The stability of the proposed compliance controller has been successfully tested with a 35 kg dummy. A video can be watched online at (`http://www.car.upm-csic.es/fsr/egarcia/ATLAS.html`).

5 Conclusions

The field of lower-limb active orthosis is mature enough to propose the next step in evolution. Taking the traditional ideas in biped robotics, we have developed an active orthosis that can modify its gait parameters such as step height, body height or step length while walking. A more versatile and comfortable active-orthosis is achieved. This goal is achieved through a compliance-adaptive control with the aid of insoles force feedback. The locomotion controller determines desired foot forces to support the user and follows a center of pressure path and the gait parameters are changed by the force sensing in the insoles. Reference positions and speeds that achieved these new gait parameters are soft enough, to

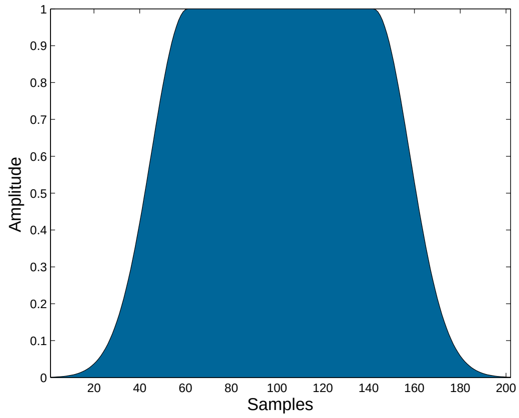
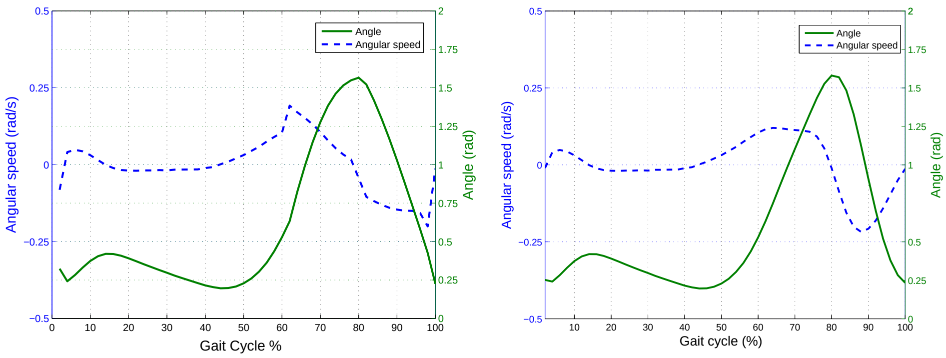


Fig. 6. Gaussian windows to modulate the path.



(a) (b)

Fig. 7. Angles and speeds at the knee when the gait is modified to provide larger ground clearance (a) without using Gaussian windows (b) using Gaussian windows.

avoid abrupt movement in the joint, through the use of Gaussian windows. The reference trajectory path is defined in a smooth way and a good performance is obtained.

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