Co-evolution of Morphology and Control of a Wearable Robot for Human Locomotion Assistance Exploiting Variable Impedance Actuators

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Abstract

The basic idea underlying this research is that the performances of wearable robots (WR) might be improved by optimizing the dynamics of the system comprised of the robot and the human body wearing it. This problem is not amenable to analytical investigations, and it asks for suitable numerical techniques able to simultaneously account for both robot mechanical structure dynamics and control laws. This paper presents on-going research efforts oriented to demonstrate a novel methodology for the design of an active lower limbs orthosis.

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1. Introduction

The most followed route in the design of WRs has been that of replicating as much as possible the kinematic structure of the human limbs. However, leaving open the mechanical design can lead to significant improvements in the dynamical performances of such machines. Kinematic incompatibilities can cause the exchange of unwanted interaction forces. Such incompatibilities can be avoided if there is no need to align the axis of rotation of the robot, as occurs for non-anthropomorphic WRs [1]. With regards to dynamical properties, studies on the legged locomotion of biological and artificial agents demonstrated a reduction in the complexity of the control and an increase in locomotion efficiency obtained by hard-wiring in the mechanical structure some or most of the desired dynamical features exploited during locomotion [2,3]. The problem of designing from scratch a non-anthropomorphic WR can be too complex to be solved by relying only on conventional design techniques. This paper presents a systematic methodology for the design of a WR for the lower limbs, based on the co-optimization of robot mechanical structure and control system.

2. Methods

The design process is divided into three stages. In the first stage a systematic search of all plausible independent generalized kinematic solutions (i.e. topologies) is performed. In the second stage, a Particle-Swarm Optimization algorithm [4] is used to define the morphologies providing the best performances in terms of some design objectives.
In the final stage, the best morphologies are compared by human designers to define the fittest solution. This systematic approach assures that all interesting generalized solutions are evaluated before producing the final design.

2.1. Simulation Environment

The simulation environment in which the WR is optimized consists of an ODE based physics simulator (Webots, [5]). The human is modeled after an adult human subject constrained in the sagittal plane. The lower limbs are modeled by 3 revolute joints (hip, knee and ankle) while the upper body is modeled as a single mass. To further reduce the problem of stability and to make the problem tractable, the trunk of the model is constrained such that it cannot rotate.

2.2. WR Structure

A novel graph-based method for the exhaustive enumeration of the generalized kinematic chains of planar non-anthropomorphic wearable robotic orthoses has been developed. The method includes two special tests (i.e. the HR-isomorphism test and the HR-degeneracy test), purposely devised to solve the problem of enumerating wearable robots kinematic structures [6]. The method allowed to exhaustively list all the independent kinematic structures of a planar kinematically-compatible wearable hip-knee robotic orthoses. In this study we focus on WR structures consisting of 4 links and 2 Degrees of Freedom (DOFs) to assist hip and knee flexion and extension.

2.3. Actuation and Control

Two actuators per leg are included so to support each of the allowed DOFs. We used a systematic algorithm to deduce all possible couples of joints which fully determine the kinematics of the system.

Each actuated joint is controlled by a visco-elastic control law. Non-actuated joints are modeled by torsional spring/damper systems of which the spring and damping constants are optimized. Each actuator consists of 3, time varying, optimized control signals: the reference trajectory, stiffness and damping. Each control signal is a third order, piecewise monotonic, polynomial interpolated from optimized data points. Furthermore, the control is modeled as a coupled dynamical system taking advantage of the intrinsic synchronization and stability properties.

2.4. Optimization

The optimization algorithm is an extension of PSO [4], allowing the algorithm to efficiently optimize the joint placement of the actuators. We optimize the morphology, actuator placement, actuator control signals, WR passive joint properties and mass distribution. The objective function to be optimized is based on the minimization of the actuator torque and the minimization of the joint angle error of the human knee and hip joint, with respect to a recorded trajectory of free walking.

3. Preliminary Results

A large variety of solutions restoring the physiological gait are found. Preliminary analysis of the co-evolved morphologies and control suggests that certain topologies yield the best fitness values, although results are sensitive to initial conditions. Additional criteria such as the wearable robot mass, mechanical feasibility, constraint forces and structure complexity further reduce the total set of satisfying solutions. The most efficient solutions require a peak torque around 100 Nm, for at least one actuator, but show significant reduction in overall actively produced torque due to leverage of the passive dynamics of the system.

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References


