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Design of personalised active orthoses for spinal cord-injured subjects based on optimal control prediction of assisted walking motions

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Abstract

Spinal cord injury (SCI) is prevalent in society. Worldwide each year between 250.000 and 500.000 individuals suffer SCI [1]. Walking impairment after injury leads to a decreased quality of life and other serious health conditions and carries substantial health care costs. Gait restoration is a high priority among such individuals. For those with incomplete SCI, the use of active orthoses (or exoskeletons) can improve the energy cost and aesthetics of their gait [2].

The authors are working on a project that aims to develop an active knee-ankle-foot orthosis (KAFO) to assist the gait of patients who retain some control of hip muscles but lack control of knee and ankle muscles due to the injury. The passive structure of the orthosis is tailored to the subject and built in an orthopaedic workshop. Then, an electrical actuator is added to the knee joint and an inertial measurement unit (IMU) is attached to the shank support to detect gait events. The user wears a backpack with an embedded system (acting as a state machine), the actuator driver, and a battery [3]. The orthosis control algorithm is implemented in two layers. The internal layer consists of a PID controller that keeps the knee extended during stance phase and performs a predefined flexion-extension cycle during swing phase. To detect when swing phase must be triggered, an outer algorithm based on the IMU measurements is used. Figure 1 shows the robotic orthosis prototype, a test subject wearing it on both legs, and the patient-specific multibody model for simulation.

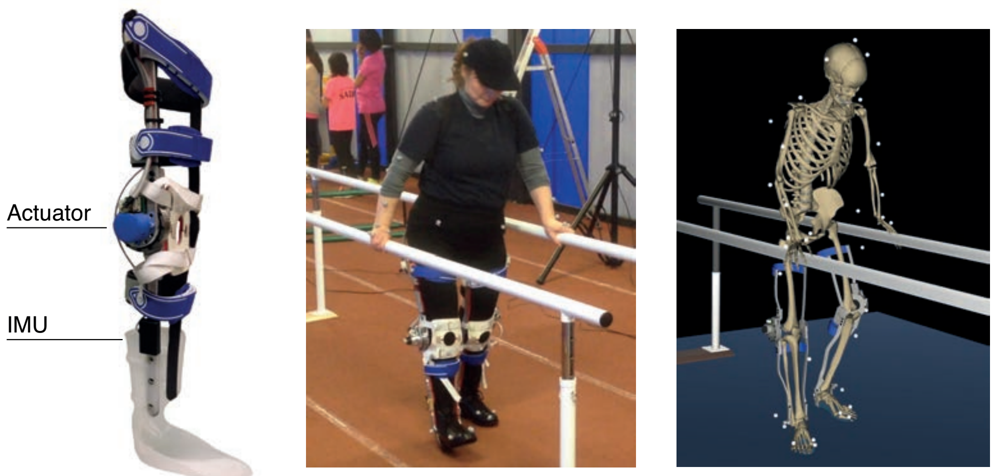

Figure 1: Active orthosis prototype (left), test subject wearing the designed orthoses (middle), and patient-specific multibody model (right).

This work presents a computational framework to predict dynamically consistent walking motions, i.e., without a residual wrench acting on the pelvis, of an SCI subject assisted by orthoses and crutches. The simulation is generated by solving an optimal control problem in which both model kinematics and driving forces/torques are unknowns.

The problem formulation for tracking an experimental motion of an SCI female subject (41 years old, mass 65 kg and height 1.52 m) with injury at the T11 level wearing a pair of passive knee-ankle-foot orthoses and crutches is first presented. Motion capture involves tracking 43 optical markers using 12 infrared cameras (Natural Point, OptiTrack FLEX:V100). Foot-ground and crutch-ground reaction forces are collected using two force plates (AMTI, AccuGait) and instrumented crutches, respectively. The dynamic skeletal model is based on the 3D full-body model from [4], developed in OpenSim [5] and scaled to the specific SCI subject. In our formulation, the optimization cost function includes terms that track experimental joint angles, joint angular velocities, and inverse dynamic joint torques, along with a term that minimizes joint angular accelerations. The equations of motion of the multibody system, obtained from OpenSim, are solved implicitly and introduced as algebraic path constraints.

With the aim of predicting new walking motions of the same subject using the above-mentioned active KAFO, we have modified the previous model and optimal control formulation. Contact models have been added to reproduce foot-ground and crutch-ground contact forces during the predicted motion. Regarding the formulation, the dynamic parameters of the knee control algorithm have been added as design variables. In addition, the cost function includes new terms that minimize the energetic cost of walking and penalty terms that prevent large pelvic tilt, leg circumduction, and lateral centre of mass displacement (which are some outcomes that have been observed in the pilot trials with the mentioned SCI subject). The presented computational methodology is intended to serve as a support tool for the patient-tailored design of walking assistive devices.

Acknowledgement

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