Personalisation of Active Orthoses for SCI Subjects using Optimal Control Predictions

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The authors are working on the personalisation of an innovative low-cost, lightweight, and easy-to-use active orthosis to facilitate over-ground walking with crutches by individuals with spinal cord injury (SCI) who possess remaining hip function. Personalisation will involve selection of the best knee motor control strategy for each subject, using predictive walking simulations that combine OpenSim patient-specific models with GPOPS-II optimal control predictions. In the present work, we describe a direct collocation optimal control framework to obtain a dynamically consistent walking motion that reproduces experimental measurements.

1. Active orthosis description and functioning

The developed device (Fig. 1a) consists of three modular components: an actuation system (motor plus gearbox) at the knee, an inertial measurement unit (IMU) at the shank, and a backpack containing the electronics and power supply [1]. The actuation and sensor modules are installed on existing passive orthopaedic supports, which are owned by SCI subjects who cannot control movement of their knees or ankles. 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 knee flexion-extension must be triggered at initial swing, an outer algorithm based on the IMU measurements is used.

2. Experimental data and OpenSim model

The experimental walking motion of a male SCI subject (39 years old, mass 72 kg, and height 1.72 m) with incomplete injury at the T11 level was measured with the subject using crutches and wearing a pair of passive knee-ankle-foot orthoses (Fig. 1b). Motion capture involved tracking 43 optical markers using 12 optical infrared cameras (Natural Point, OptiTrack FLEX:V100 sampling at 100 Hz). Foot-ground reaction forces were collected using two force plates (AMTI, AccuGait also sampled at 100 Hz) and crutch-ground reaction forces were measured using instrumented crutches.

A dynamic skeletal model was constructed in OpenSim [3] starting from the 3D full-body model reported in [2]. The model was scaled to the subject's dimensions using the OpenSim Scaling Tool. Orthoses and crutches were modelled as being rigidly attached to the lower limb segments and forearms, respectively (Fig. 1c). Marker trajectories and foot- and crutch-ground reaction wrenches were used as inputs of the Inverse Kinematics and Inverse Dynamics Tools in OpenSim. Outputs were used to define the reference experimental curves required by our optimal tracking problem.

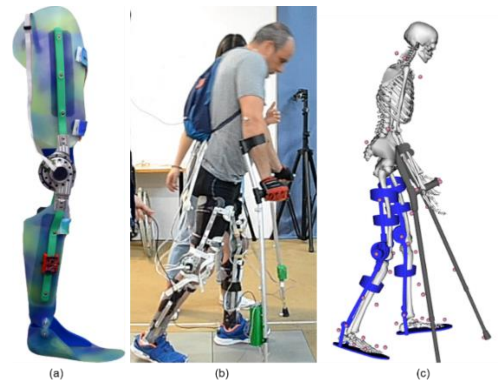

Figure 1: (a) Active orthosis prototype. (b) SCI patient wearing a pair of active orthoses. (c) Computational model of the patient.

3. Optimal control tracking framework

We have formulated a direct collocation optimal control framework to obtain a dynamically consistent walking motion that is as consistent as possible with the subject's experimental walking data. Dynamic consistency required eliminating the residual wrench acting on the pelvis (model root segment) while tracking the subject's experimental marker trajectories as closely as possible and satisfying skeletal dynamics [4,5].

The optimal control problem was formulated as a data-tracking problem. The states are joint coordinates ($\boldsymbol{x}$), velocities ($\boldsymbol{v}$) and accelerations ($\boldsymbol{a}$);

and controls are joint jerks ($\boldsymbol{j}$). The cost function minimises the squared differences between predicted and experimental joint coordinates and also the squared joint jerks (Eq. 1). Dynamic constraints are simply relations between design variables (Eq. 2). The equations of motion of the multibody system, obtained from OpenSim, are solved implicitly and introduced as algebraic path constraints. Deformable ground contact models were not included in the present problem formulation, and instead the experimentally measured foot- and crutch-ground reaction forces were applied directly to the model. To ensure correct foot and crutch placement on the ground, we included a path constraint that limited errors in foot and crutch marker positions to be within a specified tolerance.

$$[MIN] \int \left[\left(\boldsymbol{x} - \boldsymbol{x_{exp}}\right)^2 + (\boldsymbol{j})^2 \right] dt \qquad \text{(Eq.1)}$$

$$[\dot{\boldsymbol{x}}, \dot{\boldsymbol{v}}, \dot{\boldsymbol{a}}] = [\boldsymbol{v}, \boldsymbol{a}, \boldsymbol{j}] \qquad \text{(Eq.2)}$$

We solved this optimal control problem using GPOPS-II, a general-purpose MATLAB-based software for solving multiple-phase optimal control problems [6].

4. Results and discussion

We have obtained an optimal solution where the joint coordinates were slightly modified (Fig. 2) and the residual wrench was greatly reduced (Table 1). Mean RMSE is 4.5º for joint angles and 2.3 cm for pelvis translations. Pelvis and lumbar rotations are the two coordinates with the largest errors, while right and left hip flexion are the two coordinates with the smallest errors.

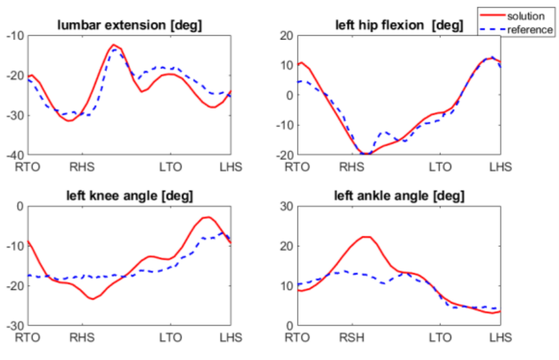

Figure 2: Torso and left leg joint angles in the sagittal plane. Experimental curves are in dashed blue lines, and optimisation curves are in solid red lines. R/LTO and R/LHS indicate right and left "Toe off" and "Heel strike", respectively.

The optimal control formulation presented in this work will be further extended for the prediction of assisted gait by modifying the cost function and introducing foot- and crutch-ground contact models. This framework may allow us to develop a support tool for patient-tailored design of walking assistive devices.

	Fx	Fy	Fz	Mx	My	Mz
(1)	7.62	33.17	14.00	1.60	6.25	0.96
(2)	1.00	4.87	1.00	0.10	0.10	0.10
(3)	86.88	85.29	92.85	93.76	98.40	89.68

Table 1: (1) RMS of residuals obtained using the reference data. RMS of forces are expressed in N, RMS of torques are expressed in Nm. Axes are: x anterior-posterior, y vertical, z lateral-medial. (2) RMS of residuals obtained in the optimal solution. (3) Reduction of RMS in %

5. Future work

Our next step is development and calibration of foot- and crutch-ground contact models. At that point, we will develop a predictive torque driven framework of the SCI subject assisted by the active orthoses and crutches. Different control strategies will be tested by modifying the amplitude, shape, and timing of the knee angle trajectory during stance and swing phase.

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