Optimal Control Prediction of a Dynamically Consistent Walking Motion for a Spinal Cord-Injured Subject Assisted by Orthoses

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Abstract

Gait restoration is a high priority among spinal cord-injured (SCI) individuals. For those with incomplete SCI, the use of active orthoses (or exoskeletons) can improve the energy cost and aesthetics of their gait [1]. The authors are working on a project aimed at developing an active knee-ankle-foot orthosis (KAFO) to assist the gait of incomplete SCI subjects that can control hip rotation to some extent. The passive structure of this orthosis is tailored to the subject and built in an orthopedic workshop. Afterward, the actuation system and sensors are added to the passive structure to make the orthosis active and autonomous [2]. Simulations using subject-specific computational walking models that account for individual impairment can help in the selection of optimal gait-assistive devices for individual SCI subjects. This work deals with the development of a subject-specific simulation framework for the prediction of dynamically consistent walking motions of an SCI subject using orthoses and crutches.

Thus far, few published studies dealing with human motion prediction involve impaired or assisted motion. As examples, in [3], walking motions at different speeds for an individual post-stroke are predicted using a detailed subject-specific model, whereas in [1], the gait of an SCI subject assisted by active orthoses is studied. In the latter, the SCI impairment was modelled at the muscle level using muscle denervation parameters. However, a generic 2D computational model that does not correspond to a particular subject was used and the active orthoses were modelled as embedded in the lower limbs, omitting the physical interaction between the subject's body and the orthoses.

This work predicts a dynamically consistent walking motion, i.e., without a residual wrench acting on the pelvis, of an SCI subject assisted by passive orthoses (with no motors and sensors) and crutches. The simulation was generated by solving an optimal control problem that tracked experimental motion, were both joint angles and joint torques were unknowns. This approach allowed us to obtain a new motion that was close to the experimentally measured one, while also minimizing the pelvis residual wrench.

The experimental walking 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 was captured. Motion capture involved tracking 43 optical markers using 12 optical infrared cameras (Natural Point, OptiTrack FLEX:V100 sampling at 100 Hz). Ground reaction forces were collected using two force plates (AMTI, AccuGait also sampling at 100 Hz) and crutch-ground reaction forces were measured using instrumented crutches (Fig. 1). The skeletal model was based on the 3D full-body model from [4], developed in OpenSim [5] and scaled to the specific SCI subject.

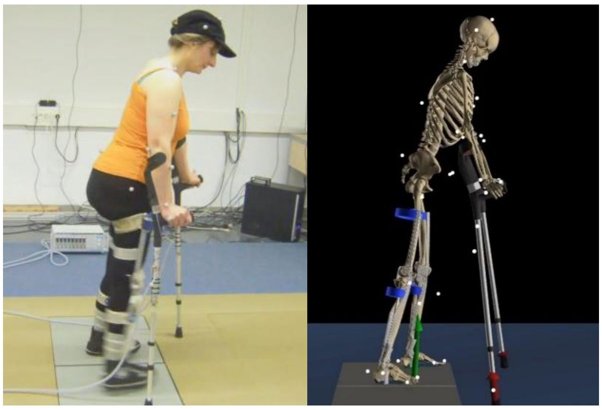

Fig. 1. Gait of the SCI subject assisted by passive orthoses and crutches: experimental motion and computational model.

The optimal control problem was formulated as follows: Find joint angles $\boldsymbol{q}(t)$, joint angular velocities $\boldsymbol{v}(t)$ and joint angular accelerations $\boldsymbol{a}(t)$ (states, $\boldsymbol{x}(t)$), and joint angular jerks $\boldsymbol{j}(t)$ and joint torques $\boldsymbol{\tau}(t)$ (controls, $\boldsymbol{u}(t)$), which minimize differences between experimental data and predicted motion (cost function), subject to satisfying the dynamics equations (constraints). The cost function included terms that tracked experimental joint angles, joint angular velocities, joint angular accelerations and inverse dynamics torques, and a term that minimized joint angular jerks. The dynamics of the problem was formulated by simple dynamic constraints, where the states derivatives are part of states and part of controls (1). The equations of motion of the multibody system, obtained from OpenSim, were introduced as algebraic path constraints, where residuals were constrained to be zero (2) and torques obtained from inverse dynamics and torques guessed as controls were equated (3).

$$\dot{\boldsymbol{x}}(t) = [\dot{\boldsymbol{q}}(t), \dot{\boldsymbol{v}}(t), \dot{\boldsymbol{a}}(t)] = [\boldsymbol{v}(t), \boldsymbol{a}(t), \boldsymbol{j}(t)] \tag{1}$$

$$-\boldsymbol{\varepsilon}_0 \leq \boldsymbol{R}_{pelvis} \leq \boldsymbol{\varepsilon}_0 \tag{2}$$

$$-\boldsymbol{\varepsilon}_1 \leq \boldsymbol{\tau}_{IDA} - \boldsymbol{\tau} \leq \boldsymbol{\varepsilon}_1 \tag{3}$$

The optimal control problem was solved using GPOPS-II [6], an algorithm that uses a direct collocation method. Due to inaccuracies introduced during the experimental data collection and in the computational modeling, the total external reactions computed from the dynamic equations do not coincide with the ground reaction forces measured experimentally, i.e., the wrench applied to the six degrees of freedom (position and rotation) of the pelvis (base body) is not zero. Motion prediction allows slightly modifying the acquired motion and forces in order to minimize the pelvis residual wrench, resulting in a dynamically consistent subject-specific crutch walking motion.

As future work, the proposed methodology will be used to predict the walking motion of the same subject wearing a pair of active KAFOs, identical to the ones presented in [2]. In this case, the knee flexion-extension provided by the orthosis actuator will be allowed during swing phase; and it will be constrained during stance, as with the real prototype. This methodology could be useful as a support tool for the patient-tailored design of walking assistive devices, to simulate patient adaptation to the device, and to test virtually different control strategies.

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References

[1] D. García-Vallejo, J. M. Font-Llagunes, and W. Schiehlen. Dynamical analysis and design of active orthoses for spinal cord injured subjects by aesthetic and energetic optimization. *Nonlinear Dynamics*, 84(2): 559-581, 2016.

[2] J. M. Font-Llagunes, D. Clos, U. Lugris, F. J. Alonso, and J. Cuadrado. Design and experimental evaluation of a low-cost robotic orthosis for gait assistance in subjects with spinal cord injury. In J. González-Vargas *et al.*, editors, *Wearable Robotics: Challenges and Trends. Proceedings of the 2nd Int. Symposium on Wearable Robotics*, pages 281-285. Segovia, Spain, 2016.

[3] A. J. Meyer, I. Eskinazi, J. N. Jackson, A. V Rao, C. Patten, and B. J. Fregly. Muscle synergies facilitate computational prediction of subject-specific walking motions. *Frontiers in Bioengineering and Biotechnology*, 4:77, 2016.

[4] S. R. Hamner, A. Seth, and S. L. Delp. Muscle contributions to propulsion and support during running. *Journal of Biomechanics*, 43(14): 2709-2716, 2010.

[5] S. L. Delp, F. C. Anderson, A. S. Arnold, P. Loan, A. Habib, C. T. John, E. Guendelman, and D. G. Thelen. OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Transactions on Biomedical Engineering*, 54(11): 1940-1950, 2007.

[6] M. A. Patterson, and A. V. Rao. GPOPS-II: a MATLAB software for solving multiple-phase optimal control problems using hp-adaptive gaussian quadrature collocation methods and sparse nonlinear programming. *ACM Transactions on Mathematical Software*, 41:1-37, 2014.