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EVALUATION OF OPTIMAL CONTROL FORMULATIONS FOR PREDICTING SWING-THROUGH AXILLARY CRUTCH-ASSISTED GAIT

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INTRODUCTION

Crutches are widely used to assist gait in individuals with lower limb impairment. Walking with crutches alters both upper and lower body loading, potentially leading to discomfort. As such, it is important to study how crutch walking affects upper and lower extremity movement patterns. Computer modelling and simulation can provide answers that motion analysis cannot. For this reason, the availability of an algorithm that allows the prediction of different crutch walking patterns could be useful in order to study the impact of changing conditions on crutch walking, and could overcome some limitations of experimental studies, such as difficulty in recruiting subjects or limitation in the number of tests that can be performed [1].

Minimal research has been conducted on axillary crutch-assisted gait, compared to forearm crutch-assisted gait [2]. In this study, an optimal control framework to predict different crutch gait patterns has been developed based on [3]. We have evaluated how well two different cost functions reproduce swing-through axillary crutch-assisted experimental data from a healthy subject. The long-term goal is to use optimal control simulations to analyze new conditions that have not been captured in the laboratory.

METHODS

Gait data were collected in the Clinical Movement Assessment Laboratory (University of Calgary) from 9 healthy young male participants (25±5.6 years, 176±5.9 cm, 75.7±8.5 kg) who performed 15 swing-through axillary crutch-assisted gait trials landing on the left leg. Marker trajectories were collected for 63 markers, and no force data was recorded. For this initial study and for process development, gait data from one participant was explored.

A 3D full-body torque-driven model of the subject using axillary crutches was created starting from a published OpenSim (National Center for Simulation in Rehabilitation Research) model [4]. The model possessed 35 degrees-of-freedom (DOF), and was scaled to the subject using a neutral trial and the OpenSim scaling tool. Each axillary crutch was introduced into the model as a rigid body welded to the corresponding hand segment. Foot-ground and crutch-ground compliant contact models were implemented in Matlab (MathWorks, Inc.) using visco-elastic force models [3].

Two different optimal control problems were formulated: (1) Calibration of contact model parameter values tracking experimental joint coordinates and ground reactions from a single trial; (2) Prediction of swing-through crutch walking pattern using the calibrated contact models and without tracking any experimental quantity. In the calibration problem formulation, joint coordinates were obtained performing an inverse kinematic analysis in OpenSim, and ground reactions were obtained performing an inverse dynamic analysis in OpenSim and sharing the residual loads between feet and crutches. In the prediction problem formulation, a swing-through crutch walking pattern landing on the left leg was imposed, with cycle duration, stride length, and relative duration of foot swing and crutch swing as the free parameters. The same initial trial used for calibrating contact models was used as the initial guess. The different optimal control problems were based on [3] and solved by a direct and simultaneous collocation method using the optimal control software GPOPS-II [5].

In order to find the most suitable cost function for predicting swing-through crutch gait, two different cost functions were evaluated: (A) minimization of the sum of the squared norms of the local angular momenta and of the sum of squared joint torque changes (Eq. 1); and (B) minimization of the sum of squared mechanical power (computed for each relative coordinate) and of the sum of squared joint jerks (Eq. 2).

$$J_A = \int_{t_0}^{t_f} \left(\sum_{i=1}^{n_b} ||\boldsymbol{L}_i||^2 + \sum_{i=1}^{n_q-6} \dot{\tau}_i^2 \right) dt \qquad \text{(Eq. 1)}$$

$$J_B = \int_{t_0}^{t_f} \left(\sum_{i=7}^{n_q} (\dot{q}_i \tau_{i-6})^2 + \sum_{i=1}^{n_q} \dddot{q}_i^2 \right) dt \qquad \text{(Eq. 2)}$$

where t_0 and t_f are the initial and final simulation times, respectively; n_b is the number of rigid bodies in the model; n_q is the number of model coordinates or DOF; $\boldsymbol{L}_i$ is the local angular momentum at the centre of mass of the i^{th} body of the model; $\dot{\tau}_i$ is the i^{th} component of the vector of joint torque change $\dot{\boldsymbol{\tau}}$; $\dot{q}_i$ is the i^{th} component of the vector of joint velocities $\dot{\boldsymbol{q}}$; τ_{i-6} is the $(i-6)^{th}$ component of the vector of joint torques $\boldsymbol{\tau}$; and $\dddot{q}_i$ is the i^{th} component of the vector of joint jerks $\dddot{\boldsymbol{q}}$. Check [3] for more details on the cost function formulation.

To evaluate the performance of each cost function, RMSE were computed with respect to experimental joint angles, and simulated spatiotemporal parameters (cycle duration, relative duration of phases, stride length, crutch width) were compared against their experimental values. We considered that a predicted motion reproduced correctly the experimental data if mean RMSE for joint angles was less than 5°, being 10° the maximum for a single joint angle.

RESULTS AND DISCUSSION

Both cost functions had a similar behavior related to spatiotemporal parameters. Cycle time and stride length were under-predicted, and crutch width was over-predicted but close to the experimental value (Table 1).

Table 1. Spatiotemporal parameters for experimental data (mean ± SD from 14 trials), and predicted motion using cost function A (Eq. 1) and B (Eq. 2).

	Exp.	Cost A	Cost B
Cycle time [s]	1.17 ± 0.05	0.70	0.68
Stride length [m]	1.74 ± 0.10	1.11	1.09
Crutch width [m]	0.80 ± 0.06	0.88	0.88

The predicted joint coordinates were smoother and showed decreased ranges of motion compared to the experimental data (Fig. 1). The mean RMSE of predicted joint angles compared to the experimental trial was 7.24° (cost function A) and 6.41° (cost function B). Maximum errors were 12.61° (left shoulder flexion, cost function A) and 22.82° (left knee flexion, cost function B).

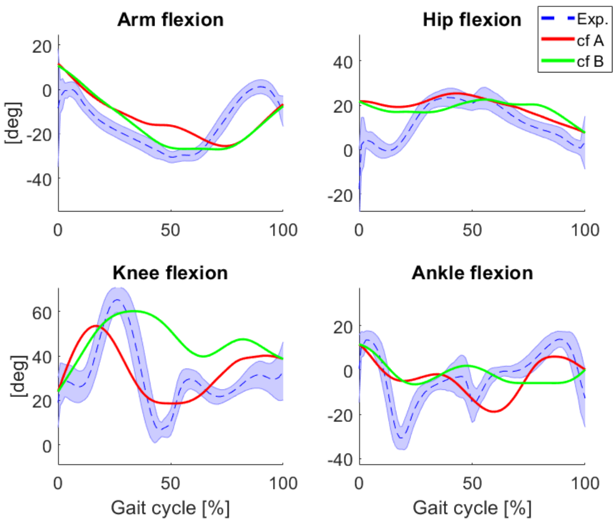

Fig 1: Relevant joint angles in the sagittal plane for the left side. In blue, experimental data (mean ± SD from 14 trials); in red, predicted motion using cost function A (Eq. 1); and in green, predicted motion using cost function B (Eq. 2).

CONCLUSIONS

The obtained results show that the optimization formulation may help predict realistic swing-through crutch gait. However, the predicted mean differences with respect to experimental motion were larger than desired. Therefore, more research regarding the cost function formulation (e.g. testing different weights for each term, adding other terms, etc.) should be done to improve results and to decrease the mean RMSE to less than 5°. For that, we will use data from all subjects.

Once the prediction framework is developed, we will study how results are affected when different conditions are studied, such as modifying the crutch length for each subject.

REFERENCES

1. Gil-Agudo, A, et al. *Clin Biomech* **24**: 551–557, 2009.
2. Fatemeh R and Kyle BR, *J Biomech* **98**: 109489, 2020
3. Febrer-Nafría M, et al. *Multibody Syst Dyn* **51 (1)**: 1-19, 2021
4. Rajagopal, A, et al. *IEEE Trans Biome. Eng* **63**: 2068, 2016
5. Rao, AV, et al. *ACM Trans Math Softw* **37**: 1–39, 2014

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