Calibration of foot-ground and crutch-ground contact models for optimal control prediction of crutch-assisted walking motions

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EXTENDED ABSTRACT

1 Introduction

Motion prediction is a field of great interest in motor rehabilitation, because it can help to determine the optimal treatment for a specific patient or to personalise an assistive device. People with mobility impairments can be assisted by orthoses and exoskeletons, and they commonly need crutch assistance for balance. Walking with crutches modifies gait kinematics and dynamics, and it requires more energy than normal walking. The choice of the proper assistive device for each patient can improve gait function. For that, it is important to have realistic multibody models of subjects assisted by crutches, which include contact models to characterise crutch-ground interaction. Existing studies that predict crutch-assisted walking have used so far simple 2D models [1,2], or have modelled the resultant dynamic effect of arms and crutches as external forces and moments applied at the shoulders [3]. Moreover, in these studies only part of the walking cycle is simulated [1,2]. In [4], a three-dimensional (3D) model of a subject assisted by upper limb crutches is driven by 3D-marker data, so a novel motion is not predicted. The aim of this work is to generate methods to predict crutch-assisted walking motions from an experimental motion capture. For this purpose, we present a 3D model of a healthy subject assisted by crutches, and we calibrate foot-ground and crutch-ground contact models.

2 Materials and Methods

We have collected experimental walking data (marker trajectories, foot-ground reaction forces and moments, and crutch-ground reaction forces) from a single healthy female subject (27 yrs., 52 kg, 1.62 m) at the Motion Analysis Laboratory of Universitat Politècnica de Catalunya (Figure 1, left). Two three-dimensional skeletal models of the mentioned healthy subject have been considered in this work: a 3D model without arms (3D HAT), and a 3D model of the subject with crutches. They possess 23 and 31 DOFs, respectively. The models have been scaled to the subject, and the two crutches have been added to the second model, initially with 6 DOF (each one) relative motion with respect to the forearm. To determine constant values for these generalized coordinates, we have performed an inverse kinematic analysis, calculated the mean value for each translational and rotational coordinate, and finally added a weld joint consistent with these mean values to replace each 6 DOF joint (Figure 1, centre).

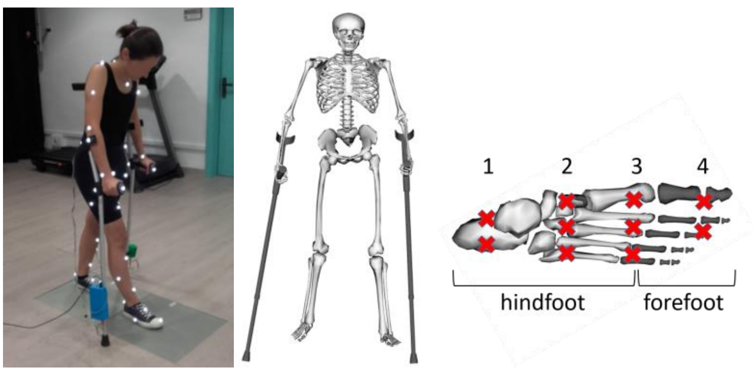

Figure 1: Left: The healthy subject during the experimental capture. Centre: The 3D OpenSim model of the subject and crutches. Right: Locations (red crosses) of the spring-damper units of the foot-ground contact models. Numbers indicate each group of spring-damper units (with same coordinate value in medio-lateral direction)

The considered foot-ground contact model consists of 10 spring and damper elements, clustered in four groups per foot (Figure 1, right). The normal force in each element is generated using a linear spring with nonlinear damping, based on [5]. The spring stiffness ($\boldsymbol{K_i}$), nonlinear damping coefficient ($\boldsymbol{c_i}$) and spring resting length ($\boldsymbol{y_0}$) have been calibrated for each group of springs. The tangential force in each element is calculated using a simple continuous and differentiable friction model. The coefficient of dynamic friction ($\boldsymbol{\mu_i}$) has been calibrated for each group of springs. The crutch-ground contact model consists of a single-point contact of a sphere at the tip of the crutch. The normal force is obtained using a Hunt and Crossley model, and initial values for parameters have been taken from [6]. The generalized normal stiffness ($\boldsymbol{K_n}$) has been considered a parameter of the optimisation, as well as the hysteresis damping factor ($\boldsymbol{\chi}$) and the sphere radius ($\boldsymbol{R_s}$). The tangential force model is the same as the foot-ground contact model, and the coefficient of dynamic friction ($\boldsymbol{\mu}$) has been considered 0.5. Both contact models have been calibrated tracking experimental data in a dynamically consistent way (i.e., with no residual actuators at the pelvis segment). First, foot-ground contact model parameters have been calibrated using the 3D HAT model, without crutches. Secondly, crutch-ground contact model parameters have been calibrated using the 3D model with crutches, using previously calibrated foot-ground contact model parameters. Symmetry has been imposed, that is, right and left feet and crutches have same parameter values.

Once contact model parameter values have been calibrated, a 3D walking motion has been predicted with the 3D HAT model. The cost function considers three terms: minimization of squared joint power, minimization of squared error in normal forces and minimization of squared joint jerk. Three phases have been considered: (1) swing phase for right foot, (2) double support, and (3) swing phase for left foot. For each phase, initial and final state values are imposed from experimental data, with a tolerance. The motion prediction, as well as contact model parameter calibrations, have been solved using GPOPS-II.

3 Results and Discussion

The foot-ground and crutch-ground contact model parameter values obtained are shown in Table 1. There are some differences among them, especially in the damping coefficient, that varies from 45.75 s/m (group 1) to $1.45 \cdot 10^{-4}$ s/m (group 2). The problem formulation could be improved modifying the cost function or adding constraints in order to avoid these large differences.

Table 1: Calibrated parameters for foot-ground and crutch-ground contact models.

	Foot-ground				*Crutch-ground*	
Parameter	*Group 1*	*Group 2*	*Group 3*	*Group 4*	*Parameter*	*Tip*
K_i [N/m]	2605	2886	4014	3563	K_n [N/m$^{3/2}$]	9666
c_i [s/m]	45.75	$1.45 \cdot 10^{-4}$	1.44	1.91	χ [Ns/m$^{5/2}$]	1.51e4
y_0 [cm]	0.75	-0.55	-1.50	-1.39	R_s [cm]	3.46
μ_i [-]	0.18	0.09	0.15	0.46		

A walking motion has been predicted using the 3D HAT model. Experimental data have been used only for the initial and final values in each phase, i.e., they have not been tracked in the optimisation. Results are consistent with the experimental data used for the calibration of the foot-ground contact model: the mean RMSE between solution and experimental data are 3.57 cm for linear coordinates, 5.26° for angular coordinates, 30.11 N for ground reaction forces and 8.74 Nm for ground reaction moments.

4 Conclusions and Future Work

Both foot-ground and crutch-ground contact model parameters have been calibrated for a specific subject and crutches using experimental motion data and an optimal control tracking algorithm. The foot-ground contact model with calibrated parameters has been used to predict a new motion with a 3D HAT model. As future work, the crutch-ground contact model with calibrated parameters, as well as the prediction algorithm, will be used to predict a crutch-assisted walking motion. In this case, four phases will be considered: (1) swing phase for left crutch, (2) swing phase for right foot, (3) swing phase for right crutch, and (4) swing phase for left foot. Within two phases, both feet and both crutches stay in contact with ground, which will be considered at the end of each phase.

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