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SIMULATION OF A SYMBOLIC HUMAN GAIT MODEL WITH AN ELLIPSOIDAL FOOT-GROUND CONTACT MODEL USING DIRECT COLLOCATION OPTIMIZATION

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INTRODUCTION

Despite a large number of studies in human gait analysis, there are very few research papers on predictive human gait simulations independent of motion tracking. Predictive human gait simulation is challenging researchers to obtain sufficient accuracy and computational efficiency to support evaluative studies (e.g., model-based assistive device controllers, athlete training, prosthesis and orthosis design).

The steps of our research are: (1) to develop a symbolic 2D skeletal human model with a 3D ellipsoidal foot-ground contact model in MapleSim; (2) to formulate an optimization to identify parameters for the ellipsoidal contact model; (3) to formulate a data-tracking optimization, using the optimized contact model from step (2), to produce feasible initial guess points for a fully-predictive optimization; (4) to formulate that fully-predictive optimization to generate a fully-predictive gait simulation. All optimizations are generated using direct collocation optimal control (GPOPS-II) [1]. Steps (1) and (2) have been achieved so far. The results from step (2), i.e., the optimized contact parameters and the simulated results obtained from the contact parameter identification, have been reported as the preliminary results in this paper. The results from steps (3) and (4) will be presented in future.

To increase the prediction accuracy and computational efficiency, dynamic equations and foot-ground contact equations are developed in a symbolic form, which is not limited by numerical programming [2]. Furthermore, the foot-ground contact model is a 3D ellipsoidal volumetric contact model that better captures distributed loads than point contact models [3] and better represents the complex geometry of a foot than spherical contact models.

METHODS

Experimental gait data is required to define initial guess points and data-tracking terms for the optimization process and also to verify the simulated results. The data, extracted from [4], includes the pelvis position, the joint angles and torques of the right hip, knee and ankle, and foot-ground reaction forces (GRF) for 20 healthy young subjects (9 males and 11 females) with an age of 10.8±3.2 years, a mass of 41.4±15.5 kg and a height of 1.47±0.2 m. Angle data for the right toe joint is also required for the optimization process. Thus, a trajectory consistent with the rest of the experimental data is estimated for the right toe joint. Since human gait is bilaterally symmetric, the data for the left leg is estimated using Fourier series interpolation with a time shift on the data of the right leg.

The human model, assumed to move in the sagittal plane, includes 9 bodies and 11 degrees of freedom (DOFs). The bodies are head-arms-trunk (HAT), thighs, shanks, hind-fore-feet and toes. The joints are 3-DOF HAT-to-ground joint, 1-DOF hip joints, 1-DOF knee joints, 1-DOF ankle joints and 1-DOF toe joints. The anthropometric data of all bodies except for the hind-fore-feet and toes are determined from [5]. For the hind-fore-foot and toe bodies, mass and geometric properties are extracted from [6] and [7], respectively.

The foot-ground contact is represented by a 3D volumetric contact model [8]. Each foot is modeled by three ellipsoids: toe, fore-foot and hind-foot. Each ellipsoid has specific position, orientation and dimensions. The schematic of the model geometry is illustrated in Fig 1.

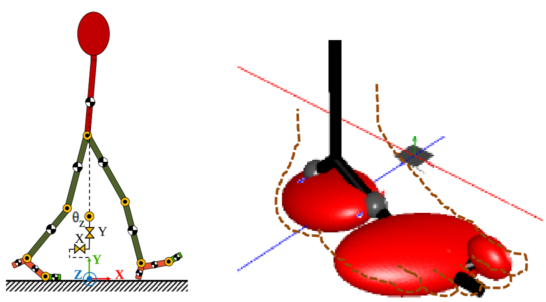

Fig 1: The human model and the contact model for the right foot.

The symbolic gait model is created in MapleSim 2018 and the corresponding equations are exported as optimized C-code to MATLAB to be used in the optimization process. The optimization process, implemented in GPOPS-II, includes three optimizations: contact parameter identification, data-tracking optimization and fully-predictive optimization.

So far the first optimization has been developed to identify contact parameters including the positions, orientations and dimensions of ellipsoids, static and dynamic friction coefficients and volumetric stiffness and damping coefficients. The optimized contact model will be used for the future two optimizations.

RESULTS AND DISCUSSION

The results from the first optimization, step (2), are illustrated in this section. We used the same optimization settings as [9] to facilitate the comparison of results.

The optimal contact parameters and the optimized contact geometry for the right foot are shown in Table 1 and Fig 2, respectively. Fig 3 shows the simulated motions, torques and GRF for the right leg, compared with the corresponding experimental data. The approximate root-mean-square (RMS) errors are 10 *N.m*, 6 *Deg* and 60 *N* for the torques, motions and normal GRF, respectively. These errors are comparable to the errors reported in [9].

Table 1. The optimal contact parameters.

Volumetric stiffness	9.6e6(N/m^3)
Volumetric damping	0.34 (s/m)
Dynamic friction	0.51
Static friction	0.60

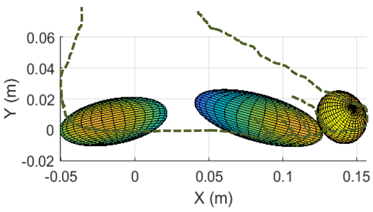

Fig 2: The optimized contact geometry.

The future work is to develop the other two optimizations, i.e., the data-tracking optimization and fully-predictive optimization. In the data-tracking optimization, gait motion is predicted by tracking the experimental data. Then the results are used as the initial guess points for the fully-predictive optimization, which will predict human gait without experimental data tracking by minimizing the energy consumed per unit distance walked. In this optimization, the experimental data will only be used in the initial guess; there will be no data-tracking term in the cost function.

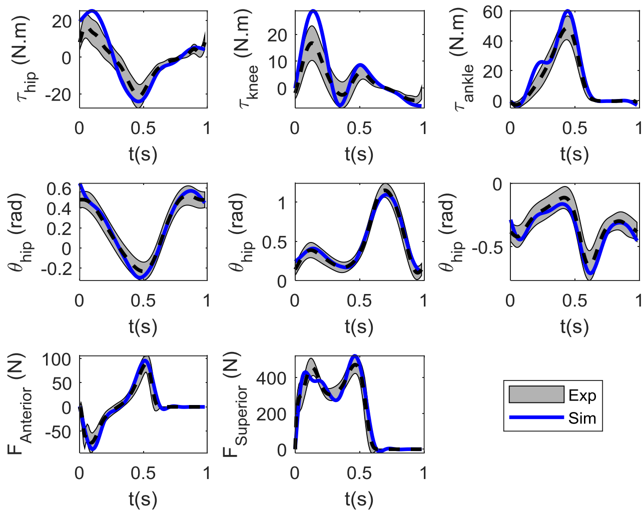

Fig 3: The simulated (solid lines) and experimental (highlighted area) torques, motions and GRF.

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