Predictive Musculoskeletal and Neuromusculoskeletal Models for Dynamic Simulation of Natural, Slow, and Fast Gaits of Children

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I. Introduction

Most of the recent predictive gait simulations focused on adults and older subjects, but clinical centers working on treatments of child gait disorders require pediatric gait simulations. In addition, the recent predictive gait simulations used an anatomically-detailed muscle model that is challenging to be fit to a specific subject. In this research, we developed computationally-efficient and physiologically-meaningful musculoskeletal (MSK) and neuromusculoskeletal (NMSK) models to simulate natural, slow, and fast gaits of children using muscle-torque-generators (MTGs), which fit specific subjects more easily than anatomically-detailed muscle models. We also evaluated the effect of different optimization cost terms on the accuracy of the predicted results.

II. Methods

We developed a 2-dimensional 11-degree-of-freedom (11-DOF) child model in contact with the ground through a 3-dimensional ellipsoidal volumetric foot-ground contact model [1]. The model includes a 3-DOF HAT-to-ground joint (HAT: head-arms-trunk segment), 1-DOF hip joints, 1-DOF knee joints, 1-DOF ankle joints, and 1-DOF metatarsal joints. The metatarsal joints are torque-driven, and the hip, knee, and ankle joints are actuated by pairs of agonist and antagonist MTGs [2]. The parameters of the MTGs were fitted to our child natural-speed gait model using a parameter identification in which the experimental gait motion data of 20 healthy children were tracked. The subjects were 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 [3].

To generate natural, slow, and fast gait simulations, we used two separate direct collocation optimal controls: "MSK-model optimization" and "NMSK-model optimization". In the MSK-model optimization, the musculoskeletal geometry and muscle contraction dynamics were represented by MTGs and the control inputs are 12 MTG activations, considering 6 MTGs for each leg. In the NMSK-model optimization, the MSK model along with muscle activation dynamics were used and the control inputs are 16 muscle excitations, considering 8 muscles for each leg. We used the MSK-model and NMSK-model optimizations to predict five different-speed gaits, including very slow walking at 0.9 m/s (XS), slow walking at 1.09 m/s (S), natural walking at 1.26 m/s (M), fast walking at 1.29 m/s (L), and very fast walking at 1.58 m/s (XL). The cost function consists of: (1) three dynamic-based cost terms, minimizing joint jerks and residual loads and solving motion dynamics implicitly, (2) a stability-based cost term, controlling the motion of the center of mass, (3) three human-criteria-based cost terms, minimizing MTG activations for the MSK model, and muscle activations and metabolic energy consumption for the NMSK model, and (4) three data-tracking cost terms, tracking the experimental joint angles, torques, and ground reaction forces (GRFs) of the natural gait (M) scaled (stretched/compressed) with respect to the cycle time of the gait we wanted to predict.

Furthermore, to evaluate the effect of different cost terms on the accuracy of the predicted results, we simulated the natural gait (M) using eight different cost functions, ranging from fully-data-tracking (FDT), having all three data-tracking cost terms, to fully-predictive (FP), tracking no experimental data.

III. Results and Discussion

The NMSK-model predicted the joint torques for the XS, S, L, and XL gaits, 17%, 12%, 10%, and 2% more accurately than the MSK-model's resultant torques. The NMSK-model could also predict muscle excitations in agreement with the EMG data and estimate cost of transport (COT) for the different-speed gaits. The COT plot (Figure 1) follows the expected 'U'-shaped curve, where the minimum COT occurs at the natural speed.

The NMSK-model with the FP cost function predicted angles, torques, tangential, and normal GRFs for the natural gait with root-mean-square errors (RMSEs) of 5.8 degree, 7.5 N.m, 15.8 N, and 62 N, respectively, which are 20%, 16%, 10%, and 8% more accurate than the results from the MSK-model with the FP cost function. Furthermore, the NMSK-model with the FP cost function predicted muscle excitations for the natural gait with an RMSE of 0.06, 12% more accurate than the resultant excitations from the NMSK-model with the FDT cost function.

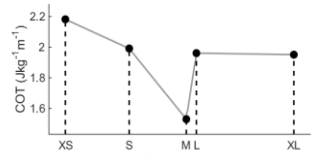

Figure 1. Cost of transport vs. gait speed.

[1] M. Ezati et al. 2020. doi: 10.1007/s11044-020-09731-3.
[2] M. Millard et al. 2019. doi: 10.1016/j.jbiomech.2019.04.004.
[3] G. Bovi et al. 2011. doi: 10.1016/j.gaitpost.2010.08.009.