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Modeling and simulation of the musculoskeletal system of the cat hind limb in Opensim

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Abstract

Introduction

Musculoskeletal models enable researchers to diagnose the causes of abnormal gait, investigate neuromuscular coordination, analyze sport movements, and compute bone-to-bone contact forces in joints, among many other possibilities [1]. One of the main drawbacks of musculoskeletal models is the lack of a clear validation of the predicted individual muscle forces. In this study, we developed a mechanically redundant musculoskeletal model for the cat hind limb, with the aim to gain insight into the distribution problem in biomechanics using Opensim [2]. The individual muscle forces calculated using this model were compared with directly measured muscle forces during free locomotion. Furthermore, model-predicted muscle activations and muscle-tendon unit (MTU) length changes were compared to the corresponding experimental data.

Methods

In the experiments, electromyography (EMG) signals, muscle forces and MTU length changes of the cat soleus (SOL), medial gastrocnemius (MG), and tibialis anterior (TA) muscles, as well as ground reaction forces were measured from five cats which were trained to walk on a walkway set at different slopes (30^o, 45^o, and 60^o up-slope) [3].

Three-dimensional skeletal model of the cat hind limb was created from computed tomography data using image processing software tools. The skeletal model with 13 DoF was consisted of five rigid bodies: the pelvis, thigh, shank, foot, and the digits. Furthermore, 25 Hill-type muscles were added to the skeletal model by taking the anatomically correct origin and insertions sites into account. Angle-dependent muscle moment arms were fine-tuned until they agreed with literature data to validate the model.

Individual muscle forces were calculated using the Computed Muscle Control (CMC) and Static Optimization (SO) tools in Opensim.

Results

Root mean square difference (RMSD) errors between the calculated and measured MTU length changes were less than 0.15 for all three muscles and movement conditions except TA during level walking, which supports the reliability of the created model.

Muscle activation patterns obtained from both SO and CMC were generally in good agreement with measured EMG data (Fig. 1a,b).

RMSD values between the calculated and measured forces for SO were consistently smaller than those for CMC for all muscles and all movement conditions (Fig. 1c,d).

Discussion

Muscle forces obtained from SO were in better agreement with the experimental data than those obtained from CMC. Good agreement between the predicted and experimental force data as well as the predicted and experimental muscle activations and MTU length changes suggests that OpenSim provides accurate muscle force predictions for cat locomotion provided that the musculoskeletal model is accurate and well developed.

References

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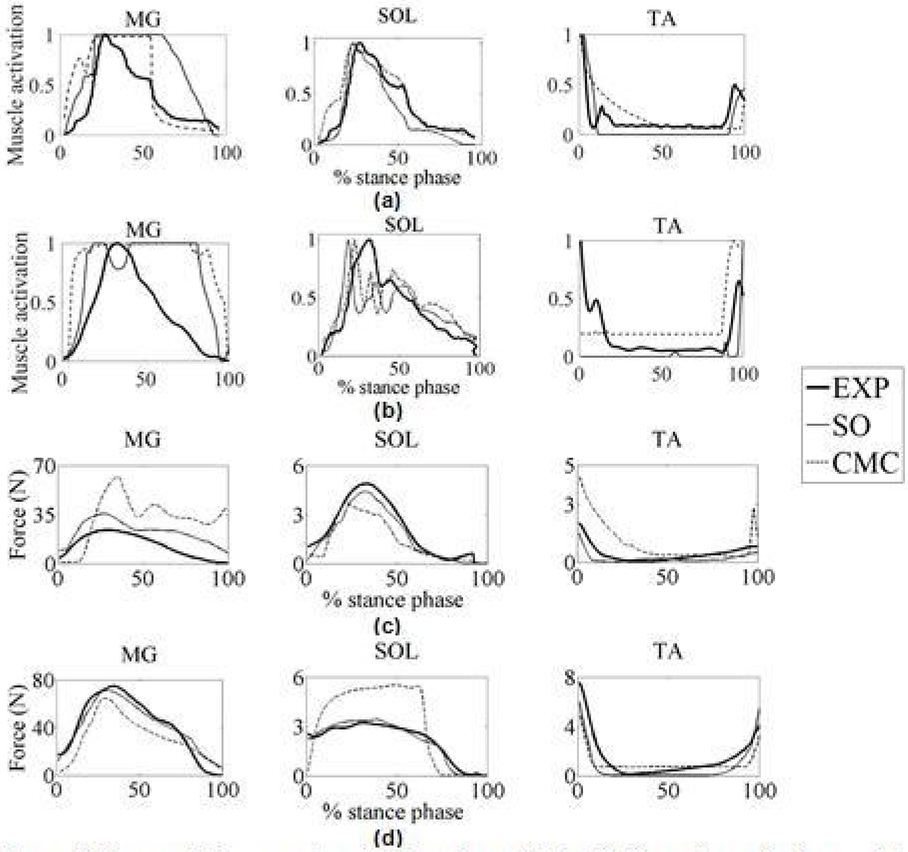

Figure 1. Measured (linear envelopes) and model-predicted activation patterns for the medial gastrocnemius (MG), soleus (SOL), and tibialis anterior (TA) muscles during (a) level walking, and (b) walking up a 60° incline. Magnitudes of the measured and model-predicted activation patterns were normalized from zero to one based upon the minimum and maximum values. Measured and model-predicted muscle forces developed by MG, SOL, and TA during (c) level walking, and (d) walking up a 60° incline. Data were normalized to the stance phases of each stride. EXP: measured muscle force; SO: muscle force predicted by static optimization; CMC: muscle force predicted by computed muscle control