INTRODUCTION

Forward dynamic simulation is a powerful tool for investigating muscle function during normal and pathological walking. However, most existing 3D muscle-actuated simulations are of short duration (e.g., half a gait cycle) due to either high computational cost or dynamic inconsistencies between experimental kinematic and kinetic data. Recent advances in controller design along with methods for reducing dynamic inconsistencies have enabled more rapid simulation of long-duration movements. The purpose of this study is to evaluate the efficacy of these new methods by generating muscle-actuated simulations of full gait cycles for multiple subjects walking over a range of speeds, and to make our simulations available to others for examination and analysis.

METHODS

Data were collected on 2 healthy adult male subjects walking at 3 speeds (50%, 100%, and almost 200% of self-selected speed) on a Bertec split-belt instrumented treadmill. A 6-camera Motion Analysis system was used to record the positions of reflective markers placed according to a modified Cleveland Clinic marker set. These movements were simulated using OpenSim (Delp et al., in press). A 3D, 10-segment, 21-degree-of-freedom musculoskeletal model (Thelen and Anderson, 2006) with 92 muscles and 41 markers was scaled to match the anthropometry of each subject. For each motion, an inverse kinematics problem was solved to compute the joint angles that minimized the difference between model and experimental marker positions.

A residual reduction algorithm (RRA) was used to reduce dynamic inconsistency between the model kinematics and ground reaction forces in each motion. Unlike previous approaches, which may apply large “residual” forces and moments from the ground to the pelvis or dramatically change torso angles to enforce dynamic consistency (Thelen and Anderson, 2006), RRA makes small changes to the torso mass center location and overall model mass and kinematics (e.g., joint angles) that result in smaller residuals. Computed muscle control (CMC) (Thelen and Anderson, 2006) was then used to estimate the muscle excitations needed to track the altered joint angles over a full gait cycle. Some muscle excitations were constrained based on EMG data (Perry, 1992) to guide CMC in generating realistic excitations.

Figure 1: A 3D muscle-actuated simulation generated from motion capture data.
RESULTS AND DISCUSSION

Each simulation was generated in less than 2 hours on a PC with a 2.8 GHz processor. Tracking accuracy was generally within 1 degree for all joint angles. However, for the fast trials, some tracking errors were as high as 6.2 degrees and the largest RMS error was 2.9 degrees. Muscle excitations were generally consistent with EMG data (Perry, 1992) and modulated with speed. Peak activations for soleus increased consistently with walking speed (Fig. 2). Hip, knee, and ankle joint moments were generally consistent with literature data as well (Inman et al., 1981). The residual forces were reduced significantly by RRA (Fig. 3). The residual moments, which also increased with speed, were more difficult to reduce. For all trials except the fast trials, the residual moments computed by RRA were generally less than 25 Nm. For one subject’s near-200% trial, however, the peak absolute value of the sagittal plane residual moment’s magnitude was only reduced from 210 Nm to 170 Nm.

CMC has dramatically reduced the computer time needed to generate 3D simulations with complex models, but its application to movements like walking where stability must be preserved, has been limited to movements about 0.5 seconds in duration. RRA allows much longer movements to be simulated, allowing CMC to be used to simulate more activities (e.g., full gait cycles, walk to run transitions). However, RRA does not completely eliminate the residuals, especially in faster movements. Future work will focus on quantifying how large residuals can be before they affect interpretation of muscle function. Our simulations and OpenSim will be made freely available on the web for testing and use by others.

REFERENCES


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