INTRODUCTION
Simulations and dynamic optimization are powerful tools for investigation of biomechanics of movement and human-robot interaction. In this study we have developed a framework for computationally efficient simulation of bipedal walking without using experimental data, which has the potential to enable prediction of gait kinematics and dynamics and under varying conditions: nominal gait, gait with a prosthesis, or gait with an exoskeleton. Such simultaneous simulation framework for the musculoskeletal system and devices can enable a systematic approach to device mechanical and control design and significantly reduce need for exhaustive human subject testing. This framework, however, needs to be (1) computationally efficient and (2) flexible in terms of control signals to allow an estimation of human motor control.

METHODS
In this work, simulation of bipedal walking has been formulated as an optimal control problem. The proper actuation profiles for the muscles or joint torques are determined by minimizing the error between center of mass velocity and a target velocity for walking. The computational framework makes use of Simbody C++ libraries along with the musculoskeletal modeling capabilities of OpenSim. Our current model uses the OpenSim musculoskeletal model presented in [1], where it was used for simulation of a standing long jump. The model has 9 sagittal degrees of freedom and 16 muscles (each leg has eight muscles). A similar model structure was used in [2] for simulation of bipedal walking using explicitly defined feedback controllers. Figure 1 shows our model with the muscles during walking.

For the control of locomotion, two controller states have been considered, corresponding to support and swing phases, which are detected based on heel strike of the swing leg. Actuations in each state for one leg have been mirrored to the other leg. This selection reduces the number of optimization parameters. Additional states and other control scenarios can be easily incorporated in our framework. It is possible to drive the bipedal walking model through both joint actuators and muscles which helps reduce the complexity in finding the proper actuation profiles, in a modular way. It also facilitates incorporation of exoskeletons or prostheses into the model.

We have used our framework to generate bipedal walking through the actuation of ankle, knee and hip joints (six total joints). Five parameters have been used to define the actuation profile of each joint. Hence, there are 30 optimization parameters to be determined. Joint torques which are obtained using experimental data for level walking (presented in [3]) have been used to define bounds for these parameters. Covariance Matrix Adaptation (CMA) method available with Simbody has been used to perform the optimization. To speed up the optimization, proper routines have been written to terminate the forward dynamic simulation in case of irrelevant solutions or non-progressing scenarios.

Figure 1: OpenSim bipedal walking model used in predictive simulations.

RESULTS AND DISCUSSION
We have successfully used our framework for the planar simulation of bipedal walking actuated by joint torques (Figure 1). The convergence of the optimization with 30 parameters takes about 10 hours on a typical desktop computer. This is significantly faster than similar results reported by Dorn et al. [2] and Lee and Umberger [4]. However, it should be noted that differences between these works and ours make direct computation time comparisons difficult. The computational efficiency of our framework and its ability to consider additional parameters that can represent force profiles compatible with human motor control, or external devices, are highly promising.

A credible simulation of bipedal walking must produce profiles similar to those observed in experimental human gait data, as part of its validation. Pursuing repeated optimization routines, with parallelization for additional computational speed and consideration of muscle actuation rather than joint torques, to fulfill this requirement, constitutes our next step.

CONCLUSION
Simultaneous predictive simulation of human movement and devices have a significant potential for facilitating design and control of exoskeletons and prostheses. In this work we present initial results from the framework we have developed for this purpose.

REFERENCES