P33

Speed-related gait changes in reflex-based neuromuscular models with a CPG extension

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1 Introduction

To meet the challenges of developing a robust and adaptable controller for robotics and rehabilitation technology, bio-inspired controllers developed from complex musculoskeletal models of humans are one potential solution. Current approaches include using a model with virtual Hill-type muscles activated by reflexes [5], which can recreate human behavior such as joint kinematics, kinetic measures, and muscle activations. They are also robust against perturbations and environmental disturbances in simulation. These models have also been implemented on lower limb prostheses [3] and on assistive devices [4,11] with promising results in restoring walking function to impaired individuals.

Speed modulation is also important to accommodate device users with a wide range of walking ability, but reflex-based controller needs to be re-optimized at each speed of interest. This can be solved by the addition of a central pattern generator (CPG), which allows easier speed modulation by tuning the CPG amplitude and frequency [2, 9]. While Song et al. [8] demonstrated that the neuromuscular model (NMM) produces human-like cost of transport and speed-step length relation, it is unclear how the kinematic and kinetic changes compare against humans. We are interested in understanding how the model achieves changes in walking speed and if this bio-inspired model adapts to speed in a similar way to that of healthy humans.

We hypothesize that the NMM will be able to globally capture human speed-related trends (e.g. step length, joint kinematics). To test our hypothesis, we evaluate gait characteristics and joint trajectories of the NMM at different speeds. These changes in speed will be performed by optimizing the model for a range of speeds as well as adding and tuning the CPG for one optimal condition.

2 Methods

We used the sagittal-plane, reflex-based neuromuscular model with a CPG extension developed by Dzeladini [2] and compared model results against human data. The NMM is actuated by seven Hill-type muscles per leg to control the ankle, knee, and hip. This includes the tibialis anterior, soleus, gastrocnemius, vasti, hamstring, gluteus maximus, and hip flexors. Locomotion is produced by simple reflex rules, which engage depending on whether the leg is in stance or swing.

We found the optimal gait at 1.0 m/s, 1.3 m/s, and 1.6 m/s using multi-stage particle swarm optimization [7] to satisfy three cost functions in series. First the model must be able to walk at least 30 m. Next the desired speed is enforced. Finally energy is minimized using a muscle model of energy consumption and includes a penalty for knee overextension [1, 10]. This order of operation ensured a walking model before tuning for speed and energy. If the optimization was performed with energy first, predictably the model would perform no movement. 25 open parameters were tuned, including stability feedback terms (e.g. trunk reference angle), muscle feedback gains, lengths, and offsets, and muscle basal activities.

We also investigated how the NMM reflex-CPG combined model modulates speed. We added the CPGs to the hip muscles only and changed the amplitude to decrease and increase speed around 1.3 m/s. For these trials, reflexes and CPG contributed equal amounts of control.

We made qualitative assessments on joint angles, moments, and powers of the NMM with those of healthy humans found in literature. In particular, step length should increase with velocity [6]. The range of motion and amplitude of angles and moments should also be greater with speed [12].

3 Results

Optimized at three different speeds (1.0 m/s, 1.3 m/s, 1/6 m/s), the reflex-only NMM produced gait changes that generally resembled human behavior. As speed increased, step duration also decreased from 0.73 s to 0.61 s to 0.48 s, as also found in humans [6]. The slowest speed also had the shortest step length, but the two faster speeds had similar step lengths. This implies that as speed increased, the step duration decreased too quickly, leading to a smaller step length than found in humans.

Joint angle and moment trajectories for the reflex-only model (Figure 1) were similar to human but did not show a clear increase in magnitude demonstrated by Zelik et al. (see Fig. 2 in [12]). The fastest speed, however, did exhibit the largest peak angle in ankle plantarflexion, knee flexion, and hip flexion. Similar results were found in the joint moments, where the fastest speed produced the largest hip extensor moment, but other no clear speed-related trend was found.

Setting the CPG amplitude of the hip swing muscles to 0.86 yielded a walking speed of 1.24 m/s. Using 1.28 CPG amplitude caused the model to walk at 1.32 m/s. Imposing greater or lower CPG amplitudes than this range caused the model to fall. Hip joint measures changed minimally about the nominal speed of 1.3 m/s (Figure 1).

4 Discussion

We showed that the NMM could reproduce gross speed-related trends in human behavior, but not specific trends in joint kinematics and kinetics. We also did not find significant changes with CPG induced speed changes, possibly because the two walking speeds created by the CPG were only a 5% change in speed at maximum.

The scaling of angle and moment magnitudes were not apparent in the reflex-only model. This is likely due to the results at 1.0 m/s. Past studies have found that the NMM has difficulties finding optimal gaits at slow speeds [2]. One possibility is that the solution presented here is not the minimum cost solution. Further optimizations are needed to assess gait at this speed.

We also found that faster speeds did not necessarily create longer strides. This was surprising because application of this controller on a knee and hip exoskeleton created a longer step length with increased speed than normally produced by humans [11]. However, this was tested on paraplegic subjects, who required body weight support. This could have artificially created a longer step length.

There were also no restrictions on the parameters to meet the fitness function. Further constraints could be enforcing small parameter changes during the optimization. This may demonstrate that the parameters change smoothly to accommodate new speeds, as it is probably unlikely the central nervous system would produce speed changes by gain scheduling with large parameter variations.

Future work includes using cost of transport, instead of energy, in the cost function and evaluating NMM gait at other speeds. More drastic speed changes by further tuning of the CPG amplitude and frequency is needed for a better comparison of reflex-only gait and CPG-influenced gait. Understanding how this complex but versatile controller behaves allows further insight into its application in robotics and assistive devices.

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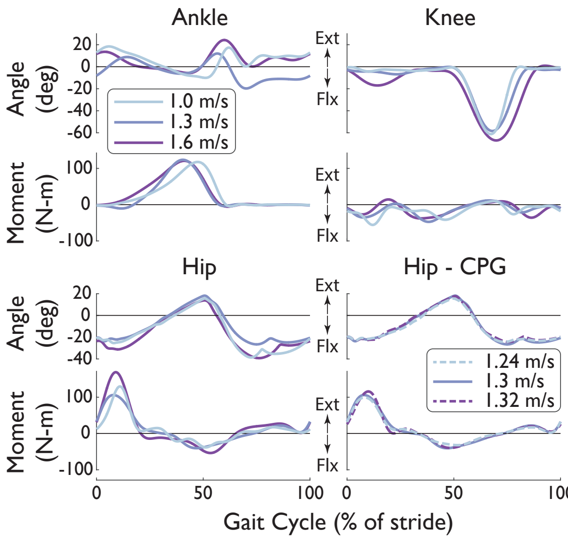

Figure 1: Joint angles and moments at different walking speeds for the reflex-only NMM (solid lines) and with CPG modulation (dashed lines).

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