Control Optimization of Human Walking

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Introduction

Dynamic simulation subject to optimality principles serves as a powerful tool for uncovering underlying principles of human movements [1]. Optimization of energy consumption often leads to predictive simulation of neuromuscular skills, such as walking, running and jumping. Combining dynamics and optimization is a non-trivial task, so relevant techniques have evolved over the last three decades to establish two major approaches, called *static and dynamic optimizations*. Static optimization based on inverse dynamics has been used extensively to estimate muscle forces during gait. Dynamic optimization, on the other hand, is based on forward dynamics simulation and thus can estimate muscle activations more precisely and predict gait patterns based solely on assumed optimization criterion, though the effectiveness of dynamic optimization with respect to static optimization is not justified for normal gait [2].

Yet another category of approaches emerged recently by exploiting open-loop forward dynamics simulation with balance feedback control [3, 4]. Unlike dynamic optimization that generates a single gait pattern as a solution of optimization, the approaches in this emerging category construct optimized control policies (or feedback controllers) of muscle-actuated skeletal models, which walk energy-efficiently while maintaining their balance during gait under external perturbation. We call the emerging approach *control optimization*. The question is if control optimization helps understand underlying principles of human walking.

To answer the question, we begin with the argument that human walking is not energy optimal. The optimal motion consumes just enough energy and thus can be fragile even under mild perturbation. Any biological motion consumes more energy than bare sufficiency for improved stability and robustness in the form of co-contraction of agonist and antagonist muscles. From the simulation point of view, an optimized control policy equipped with balance feedback consumes more energy than a single optimized gait pattern does.

We conducted experiments that demonstrate the sufficiency of energy consumption in human gait using optimized control policies of a musculoskeletal dynamic model.

Methods

Our dynamic model has a lumped upper body and two legs with 25 joint DOFs and 92 Hill-type musculotendons. The model is 180 cm tall and weighs 75 kg. We use a control optimization method presented by Lee et al. [3] to construct a family of control policies parameterized by step length and frequency. Optimization of control policies can compute preferred step length and frequency for any choice of optimization criteria.

Our control policies can take optimization criteria that are quadratic to optimization variables including joint acceleration and muscle activation.

$$\min \int \left(w_1 \|a\|^2 + w_2 \|\tau\|^2 + \mathrm{E} \right) dt$$

Our optimization criteria include two major terms, total muscle activation $\|a\|^2$ and total joint torque $\|\tau\|^2$ integrated over time. The criteria also include auxiliary terms E minimizing ground reaction force, joint tracking error, and end-effector tracking error to regularize the optimization process.

We compare two test cases with different optimization criteria. The first case with $w_1 = 500$ and $w_2 = 0$ assumes a relaxed or tired body condition. In Case I, minimizing muscle activation (or energy consumption) is a major goal of optimization, discouraging co-contraction of agonist and antagonist muscles. The second case assumes a healthy and energetic body condition with $w_1 = 0.5e - 10$ and $w_2 = 0.1$. In Case II, torque-minimization plays a major role, while muscle activation serves as a weak regularizer. Co-contraction of muscles around a joint provides stability, but does not affect torque measured around the joint. It means that torque-optimization does not penalize muscle co-contraction and potentially constructs more stable control policies suitable for an energetic body condition.

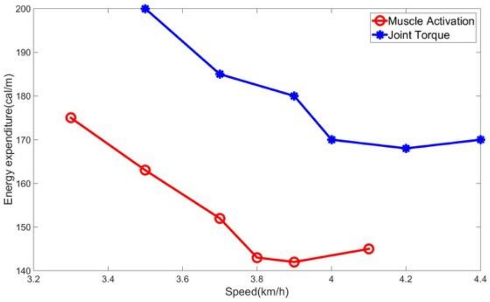

Figure 1. Speed-energy graph of optimized control policies. The y-axis represents metabolic energy expenditure normalized by the distance traveled.

Results

As expected, minimizing muscle activation (Case I) generates control policies more energy-efficient than torque-minimizing control policies (Case II) at all speeds (Figure 1). An optimal walking speed is predicted at 3.9 km/h with muscle-activation optimization, while the predicted speed is higher at 4.2 km/h with torque optimization. Probably, higher energy consumption rates and improved stability allows faster walking speed.

We also conducted a simulation experiment to evaluate the stability of control policies at the presence of external pushes ranging from 20 N to 100 N. The muscle-activation-optimized control policies were resilient against up to 30 N of external pushes, while the torque-optimized control policies withstood up to 80 N. This experiment confirms that there exists a tradeoff between energy-efficiency and stability.

The optimized control policies can also predict step lengths with respect to walking speeds. In the Case I, the predicted step length is the largest when walking speed is optimal, meaning that humans have to take short strides to walk slower or faster than the optimal speed. The Case II shows a two-phase trend that the step length increases up to a threshold speed and goes steady above. This plot matches better with observations in previous studies, though previous studies on speed-stride relations are mostly on running [5]. Humans during gait speed up by increasing step length at slow pace. At fast pace, the step length stays steady and speedup is achieved by increasing step frequency.

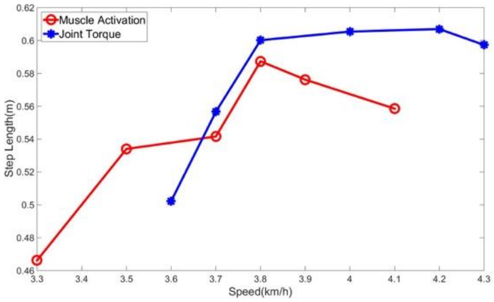

Figure 2. Optimal step length plotted as a function of walking speed.

Discussion

Our experiments demonstrate that control optimization with appropriate criteria can estimate joint stiffness and gait stability in human walking. The design of the current study allows a comparison of criteria for control optimization. The design of optimization criteria is related to the modeling of body conditions, ranging from relaxed to energetic.

The predicted walking speed (4.2 km/h in Case II) in our simulation study is slower than the predicted speed in previous studies (4.8 km/h in [1]), though the parabolic tendency of our energy-speed plot is similar to previous ones. The lumped upper body in the dynamic model and the lack of arm swing are perhaps main causes of the discrepancy.

References

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