A Framework for Bipedal Walking Research in Biomechanics from Robotics

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Introduction

Bipedal walking has been a research topic in biomechanics for many years [1]. After this, many research on human bipedal walking has been conducted. Most common methods require laboratory environments with motion capture systems and force platforms. Measured data were, then, entered into bipedal walking models for further analysis. Even though this method is considered the golden rule in biomechanics, there exist limiting factors including experimental artifacts, time constraints, intractability to change experimental conditions, etc.

In robotics literature, techniques of trajectory optimization have been widely used to produce a set of joint trajectories that minimize a cost function while satisfying constraints. The benefits of these techniques include no need of experiments, no time constraints, ease of changing system parameters, to name a few. Trajectory optimization is beneficial in the biomechanics research for the following reasons. First, no experiments with subjects are needed, which involves with time, cost and, unforeseen safety issues. Second, system parameters can be easily updated without the need of repeated (or paired) experimental design, which is important for research with people with impairments. For example, the optimal reference trajectory for transfemoral amputee patients are not known due to amputation, weakening the usage of the reference trajectory from healthy subjects. Third, perturbation studies and motor control research can be easily conducted. The results from the trajectory optimization can be easily combined with various controllers in the forward simulation to perturb the walking or to test several motor control ideas (e.g., uncontrolled manifold, equilibrium hypothesis, free energy principle). Even though the results from the models need to be validated with the experiments, these can provide the intuition about the human motor control of bipedal locomotion. More importantly, the intuition learned can facilitate the expensive experiments in the more meaningful and successful directions.

In this abstract, we introduce the framework for bipedal walking research that's used in HUR group at Texas A&M University.

Methods

Trajectory optimization: There exist several approaches in the optimal control problems including Pontryagin's minimal principle (MP), dynamic programming (DP), shooting methods (SM), and direct collocation method. Each has its own benefits and disadvantages. While MP, DP and SM can provide accurate solution, they cannot be easily scaled up to cases with higher dimensions and complicated constraints. Direct collocation, however, can provide more efficient computation by discretizing the infinite dimensional domain into lower finite dimensions and using nonlinear programming algorithms (e.g., IPOPT). The compromised accuracy can be remedied by increasing the collocation points or algorithms.

Transcription methods: Both trapezoidal (TPZD) collocation and Hermite-Simpson (HS) collocation methods are used. HS is more accurate than TPZD. However, HS is slower than TPZD. Therefore, depending on the complexity of the model, either method can be selected [2]. Appropriate differentiation methods (e.g., numerical, symbolic, automatic) for dynamics and constraints need to be chosen for the best performance. When the complexity of the model increases, acceleration can be used as separate decision variables.

Dynamic models: Euler-Lagrange (EL) formulation is the usual choice for modeling the bipedal walker. EL formulation can also provide intuitive information including energies in the system, and generalized momenta. If the slipping is required, extra generalized coordinates need to be introduced at the slipping foot (note it can be anywhere in the body) and appropriate constraint dynamics should be formulated by introducing Lagrange multipliers.

Cost functions: Several cost functions have been used in the literature including cost of transport, torque squared. Depending on the complexity, relaxation terms for constraints can be added in the cost. Recently, we reported that adding extra terms (e.g., stepping time uncertainty, angular momentum) in the cost enhanced the robustness of the bipedal walking to perturbation [3,4].

Control in the forward simulation: Once optimal reference trajectories are determined, appropriate controller should be chosen. PD control is the usual choice for tracking the reference trajectories. However, more complicated control schemes are needed in many cases: i) the system is underactuated, ii) perfect trajectory tracking is needed, iii) impedance control is needed, iv) and more. In addition to PD control, we use impedance control, and hybrid zero dynamics (HZD)-based control. Specifically, HZD-based control requires the feedback linearization via desired output functions. HZD approach is useful since it can handle underactuated systems, and provides rapidly exponentially stable trajectory tracking. Lastly, it is more beneficial to use a state-based phase variable (i.e., parameterized time) to track the trajectories rather than time-based control since any perturbed movement will unrealistically correct the errors if time-based control is used. Horizontal whole body COM position normalized by the desired walking speed is a reliable phase variable.

Other considerations: When muscle activation is involved, muscle models should be included in the modeling. Direct collocation can efficiently solve this problem with muscle models included in the optimization due to its strength in scalability. In our research group, muscle models are not considered except the direct EMG measurement. Please refer to OpenSim Moco [5].

Results and Discussion

Using the introduced framework, we could generate human-like walking trajectories for healthy people [6,7] and transfemoral amputees [8,9]. We could also show that human balance and walking tried to minimize the entropy (e.g., H_∞ vs. H_2 via HZD-based control) due to free energy principle [10]. Robustness to perturbation could be enhanced by appropriate choice of cost function. Optimization performance varied depending on the optimization settings and the complexities of the problems.

Significance

The introduced framework can facilitate the biomechanics and motor control research for human bipedal walking.

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