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A Framework for Bipedal Walking Research in Biomechanics from Robotics

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RESEARCH HIGHLIGHT

- A framework for trajectory optimization is introduced for bipedal walking.
- The introduced framework can facilitate the theoretical research in biomechanics and motor control areas for human bipedal walking.

INTRODUCTION

Usual bipedal walking research in biomechanics

- Most common methods in human bipedal walking research require laboratory environments with motion capture systems and force platforms [1].
- Measured data are, 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.

Trajectory optimization from robotics

- In robotics, 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.

Benefits of trajectory optimization in biomechanics

- No experiments with subjects are needed, which involves with time, cost and, unforeseen safety issues.
- System parameters can be easily updated without the need of repeated measures (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.
- 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 model needs to be validated with 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.

METHOD

Trajectory optimization

- There exist several approaches in the optimal control problems: Pontryagin's minimal principle (MP), dynamic programming (DP), shooting methods (SM), and direct collocation (DC) 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 function spaces into lower finite dimensions and using nonlinear programming algorithms (e.g., IPOPT).
- The compromised accuracy can be cured by the increased number of collocation points or enhanced transcription methods.
- DC can be combined with MP, DP, or SM to resolve both issues of accuracy and efficiency.

Transcription methods

- Both trapezoidal (TPZD) collocation and Hermite-Simpson (HS) collocation methods are used. HS is more accurate than TPZD.
- However, HS requires more computation 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 [2].

Dynamic models

- Euler-Lagrange (EL) formulation is the usual choice in 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). Appropriate constraint dynamics should be formulated by introducing Lagrange multipliers.
- Newton-Euler (NE) formulation can be used if direct computation of all constraining and interacting forces is needed. However, analytic investigation of the system can be less viable.
- Hamiltonian formulation can be used to get the direct information on the total energy and generalized momenta. EL formulation and Hamiltonian formation can be used interchangeably.

Cost functions

- Several cost functions have been used in the literature including cost of transport, torque squared [2,3,4,6,7].
- 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 in tracking the reference trajectories.
- More complicated control schemes are sometimes needed: 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 a feedback linearization about the desired output. HZD approach is useful since it can handle underactuated systems and provides rapidly exponentially stable trajectory tracking. Note that the stable trajectory can be obtained by the direct collocation.
- Whenever contacts are involved, impedance control can be considered. During the stance phase, impedance control can be used whereas tracking control can be used during the swing phase. In addition, to accommodate unexpected terrains while tracking the desired trajectories during the swing phase (e.g., premature heel strike), reducing the control gains of the PD control helps.
- It is beneficial to use a state-based phase variable (i.e., parameterized time) to track the trajectories since any perturbed movements will cause unrealistically excessive corrections if time-based control is used. Horizontal whole body COM position normalized by the desired walking speed is a reliable phase variable [4].

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] for the open source package for direct collocation and muscle models.

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 functions (e.g., inclusion of angular momentum).
- Optimization performance varied depending on the optimization settings and the complexities of the problems [2,11].

CONCLUSIONS

- A framework for a trajectory optimization from robotics literature was introduced for bipedal walking research in biomechanics.
- The introduced framework can facilitate the theoretical research in biomechanics and motor control areas for human bipedal walking.

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References

[1] Weber W et al., Mechanik der menschlichen Gehwerkzeuge, 1836.
[2] V. Knisley, MS thesis, Texas A&M University, 2020.
[3] Chao, PhD dissertation, Texas A&M University, 2019.
[4] DeBuys et al., ASB, 2020.
[5] OpenSim Moco, https://simtk.org/projects/opensim-moco
[6] Chao et al., IROS, pp1435-1440, 2019.
[7] Chao et al., IROS, pp4848 - 4853, 2017.
[8] Paredes et al., IROS, pp3204-3211, 2016.
[9] Hong et al., ICRA, pp2838-2844, 2019.
[10] Hur et al., Scientific Reports, 9:16870, 2019
[11] Knisley et al., ASB, 2020.